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SOME EFFECTS OF CLOSED SYSTEM FREEZE-THAW CYCLES
ON A COMPACTED, HIGHLY PLASTIC CLAY.

BY

ROY DENNIS COOK.

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE
STUDIES IN PARTIAL FULFILMENT OF THE
REQUIREMENTS FOR THE DEGREE OF MASTER
OF SCIENCE.

DEPARTMENT OF CIVIL ENGINEERING

EDMONTON, ALBERTA.

JUNE, 1963.

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JUNE, 1963.

UNIVERSITY OF CALIFORNIA

FACULTY OF GRADUATE STUDIES

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "Some Effects of Closed System Freeze-Thaw Cycles on a Compacted, Highly Plastic Clay" submitted by Roy Dennis Cook, in partial fulfillment of the requirements for the degree of Master of Science.

ABSTRACT.

A compacted, highly-plastic clay was subjected to cyclic freezing and thawing. Specimens two inches in diameter by four inches in length were compacted using compactive efforts chosen to approximate both modified Proctor density and standard Proctor density. These specimens were frozen quite rapidly, using the "closed system" type of test. Specimens were tested in triaxial "quick" compression tests following compaction, and after one, three, nine and fifteen cycles of freezing and thawing. Instrumentation was provided for measuring length and volume changes of the specimen following each cycle of freeze-thaw.

The strength of compacted, highly plastic clay was found to be decreased considerably by cyclic freezing and thawing. The majority of this strength loss took place within the first three cycles of freeze-thaw. Indications from the triaxial tests were that freeze-thaw reduced the cohesion of the compacted clay but did not affect the angle of internal friction greatly.

It appears ice lensing and water migration can occur only on a limited scale under the conditions imposed by the tests. No overall moisture migration occurred in the specimens when subjected to directional freezing.

The change in volume occurring in a closed system, both during freezing and thawing, of the compacted clay used, appear to depend primarily upon the original moisture content of the soil, and secondarily upon the degree of compaction. Changes in dry density, void ratio, and degree of saturation which occurred due to freeze-thaw cycling are directly related to the volume changes which occurred.

ACKNOWLEDGEMENTS.

The author wishes to thank Dr. S. Thomson, Associate Professor of Civil Engineering, for his continuous aid in conducting this investigation, and for his helpful suggestions and constructive criticisms.

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CHAPTER I

INTRODUCTION

Since the time of the earliest pavements in areas where winter freezing was prevalent, it has been observed that ground freezing has produced rough-riding surfaces and often cracked pavements as a result of heaving. Associated with the increase in the numbers and weights of vehicles, was the occurrence of a more wide-spread and general structural failure of pavements, during the spring thawing season. The overall effect of ground freezing and thawing is referred to as the effect of frost action. Soils are spoken of as having a high or low frost susceptibility depending on the degree with which heaving, reduction in load-carrying capacity, and other physical properties are influenced by the freezing and thawing processes.

Many factors influence the intensity of frost action. Climate, location, degree of exposure, and the nature of the ground cover (including the pavement) influence the depth and rate of both freezing and thawing. The nature of the soil, its chemical and physical composition and its state, its moisture content and distribution, its porosity and its structure govern the thermal properties of the soil and influence the nature of freezing and thawing. Further, the composition and state of the soil govern the physical properties of the soil and thus influence the degree with which frost action affects load carrying capacity of the soil.

One original field of thought concerning frost heave stemmed from the fact that water increases in volume by about nine percent when it changes to ice. Between 1916 and 1930, Taber (11, 12, 13, 14,)^I. performed tests which showed that heave obtained was far greater than that which could be explained on the basis of volume change on freezing alone. He suggested that the difference was due to "ice segregation" which would occur when there was a migration of moisture to the frost line. This hypothesis was substantiated when heave occurred with a pore liquid which contracted on freezing, and the importance of the availability of water for frost heaving was recognized.

It was recognized by Taber, that the availability of water at the frost line is dependent on the existence of a source of supply within reach of the capillary rise of the material, and on the resistance offered by the material to flow from the source to the frost line. The first of these factors may be controlled in laboratory tests, and therefore, the "open" and "closed" system concepts of Taber must be considered when comparing frost heave results from independent sources.

Beskow (15) investigated the effects of freezing soils in a closed system on heaving. He discovered that the resulting heave under the conditions imposed is usually small, and that the freezing results in a marked increase of the water content in the frozen zone, causing a reduction in load carrying capacity on thawing.

I. Numbers in parentheses indicate references in bibliography.

Tests by Taber (12) and the Corps of Engineers (10) substantiated Beskow's findings and showed water migration, ice segregation, and heaving can occur in fine grained soils remote from a water table and that there is a decrease in volume in the area from which the water migrates

Taber and Beskow agreed that soils in nature seldom behave as absolutely closed systems. Taber mentioned the possibility that a closed system may exist when the water table is flat over large areas and nearly coincides with the surface.

An essentially closed system can exist under highways where the pavement prevents infiltration from the top, the ditches maintain the water table at a relatively low elevation, and the low permeability of a clay subgrade prevents any great degree of infiltration during rainfall. The fact that a highway subgrade approaches a closed system has been borne out by observations and tests of existing highways by Motl (6). He reports no startling changes in moisture content, but an abrupt springtime strength loss of about 50% in many cases. It was noted that "while the moisture content was highest just after the frost left the ground, it does not appear that the small variations from the fall values are sufficient to account for all the loss of soil stability. It is suspected that frost action attacks the stability of a soil mass by altering its structure without necessarily changing the moisture content".

I.1. The Purpose of This Investigation.

The purpose of this thesis is to investigate the effects of cyclic freezing and thawing on a highly plastic clay under conditions which, in part simulate a subgrade existing as a closed system. The conditions imposed on the clay were a completely closed system, a degree of compaction and a moisture content similar to that at which a subgrade is placed, and alternate cycles of freezing and thawing which could compare to a daily cycle of freezing and thawing in nature. The principal questions to be investigated were:

1. What is the volume change (a) upon freezing and (b) following thawing; and is this volume change sufficient to indicate ice segregation in highly plastic clay in a compacted state.

2. How is the strength of compacted highly plastic clay affected by cyclic freeze-thaw; in what manner does the strength vary with the number of cycles of freeze-thaw and; what is the cause of any strength variation.

CHAPTER II

REVIEW OF LITERATURE PERTAINING TO FROST ACTION.

In Clay Soils.

A comprehensive survey of past work in the fields of frost action and related fields to the year 1951 is available in The Highway Research Board, Special Report No. 1 (1). Consequently this review includes only those factors which relate especially to the subject of this thesis and a review of any subsequent publications.

II. 1. Frost Action.

Definition - The term frost is defined as the act or process of freezing, that is, congealing of liquids with special reference to water. Since freezing is the fundamental phase of the overall phenomenon of freezing and thawing, the term frost action is used throughout this report to denote that phenomenon.

II. 11. Factors Which Influence Frost Action.

The factors which influence frost action can be divided into extrinsic and intrinsic factors, that is, those which are outside but which act directly on the soil, and those which belong to or are properties of the soil. Extrinsic factors can be classified under climate and load in nature, and in the laboratory can be termed

freezing conditions and surcharge.

Intrinsic factors include the composition of the soil, both chemical and physical, and the state of the soil mass with regard to soil moisture content, density, and structure. They determine the thermal properties of the soil and the physical properties of the soil including load carrying capacity and the ability of the soil to move water to the freezing zone, and thus influence the amount of heave or shrinkage.

State of the Soil Mass.

The state of the soil mass, that is its moisture content and uniformity of distribution, its porosity, unit weight, temperature and structure strongly influence the nature of frost action. Of these factors, moisture content is the dominating influence in determining the magnitude of freezing and thawing effects.

Effect of Moisture Content and Distribution.

The moisture content of soil at the beginning of the freezing cycle largely determines the amount of ice segregation and the heaving of the soil during the freezing cycle. The extent to which the load carrying capacity of a soil is reduced upon thawing is determined by changes in the distribution, and/or the amount of the soil moisture, plus changes in the soil density and porosity due to ice segregation. An outside source of free water is not a requisite for frost action in soils, however, it greatly intensifies all phases of frost

7.

action.

When free water is not available, i.e. a closed system, tests (10) on the effect of the initial degree of saturation on frost susceptible soils showed that the water content at the top of the sample (when freezing from the top) varies directly as the initial degree of saturation; and the water content at the bottom decreases to a relatively constant value, independent of the initial degree of saturation. The water content in the unfrozen zone of remolded lean clay specimens decreased approximately to the shrinkage limits as water was supplied to the zone of freezing for ice-lens growth.

Effect of Porosity and Unit Weight.

Both the amount of water held in the soil and the rate of water movement of the freezing zone are controlled by the nature (size and total volume) of the soil voids. Thus frost action in a given soil depends upon the density.

Tests (10) conducted on soils having little or no plasticity, and using total percent heave in open system tests as a criterion for frost susceptibility, indicated that there is no advantage in compacting soil from the stand point of decreasing the effects of frost action. Since a few freezing cycles could cause a loosening of a highly compacted soil, the advantage of obtaining a high degree of compaction is questionable, unless the soil is made virtually non-frost susceptible by the compaction.

Effect of Structure.

Uneven soil textures may cause a variation in stratification or segregation of ice, creating non-uniform soil moisture conditions, that is, local zones of saturation. Stratification of the soil has an influence on the development of ice lenses, in that the occurrence of a very thin stratum of silt or clay in sands may cause the formation of a thick ice later. Any discontinuity in the form of a stone, crack or joint in structured soils may cause fissures, which may become filled with ice and result in widening of these fissures.

Effect of Temperature.

Tests made by The Corps of Engineers (10) showed that the rate of penetration of the 32° F. temperature does not affect the rate of heave for the range tested ($\frac{1}{4}$ to 1 $\frac{3}{4}$ in. per day) in frost-susceptible soils of various gradations. The test series, besides demonstrating that the rate of heave does not vary appreciably with rate of frost penetration, also showed conversely that the total percentage of heave of the frozen material, and the intensity of ice segregation should vary directly with the rate of freezing. Field explorations indicate that the greatest accumulation of segregated ice results from slow penetration of freezing temperatures. Thus, for example, if the rate of penetration of the freezing temperatures is reduced to one half, with the heave per day remaining constant, the heave for any one day will represent the freezing of only half as much of the original soil, and the expansion of that soil per unit

depth must be doubled, with twice as much segregated ice, in order to maintain the rate of heave.

Although there is a considerable amount of data available regarding freezing and thawing and frost penetration in relation to climatic data on highway and airport subgrades, this data is not really useful, since additional data regarding the type and state of the soil, the type of cover, and the conditions of exposure all needed are lacking.

Composition of Soil.

Chemical Composition.

Chemical composition is usually expressed in terms of content of different minerals which make up the soil fines and organic matter. Clay minerals differ greatly in the degree in which the particles adsorb water.

Grim (9) analyzed the relation of clay mineral composition to frost action by considering a soil composed entirely of each of the main minerals. Montmorillonite has a large adsorption surface area (800 sq. m./gram) since adsorption water may penetrate between individual structural units, and it therefore has a large adsorption capacity. Water adsorbed on these surfaces would consist of molecules in a definite structure and may not be mobile. The mobility of the water for montmorillonite is governed in a large measure by the nature of the adsorbed ion. Montmorillonite clays are quite impervious, and on freezing there is little or no concentration of ice in layers

due to the lack of mobility of the water.

Kaolinite particles are larger than montmorillonite (100 to 1,000 times) and surface area is relatively small. Thus at small moisture contents fluid water would be present and since kaolinite soils are not impervious, ice layers could form on freezing.

Illite - Their adsorption characteristics are of the same order of magnitude as kaolinite soils but they immobilize slightly more water.. They are not impervious and should show readily the concentration of water in ice layers on freezing.

Regardless of the most prevalent type of mineral, if the soils are dominantly fine grained, they are sufficiently susceptible to frost action to be considered dangerous. Grim points out, however, that very fine colloid-size clay materials show little or no segregation of ice on freezing.

Physical Composition.

The most common means for distinguishing frost susceptibility of soils is to relate intensity of heaving with size distribution in the fine-grain fraction. Tests by The Corps of Engineers (10), based exclusively on grain size, show that the finer the grains, or the higher the percentage of colloidal sizes contained in the fine soil fraction, the more effective the fine soil fraction is in producing ice segregation. The presence of plasticity is also an indication of the possibility of greater ice segregation.

Physical Properties of the Soil Mass.

The physical properties which permit the soil to transport moisture against gravitational forces by capillary action, or vapour movement, or to move soil water laterally or vertically under hydrostatic head or gravitational pressure, are probably the greatest single influence in determining the magnitude of frost action effects. These physical properties include the moisture content, porosity, density and grain size and distribution.

The intensity of frost action effects may be measured in terms of magnitude of volume change on freezing, either swelling or shrinkage. The relative ability of a frozen or thawed soil to resist deformation under load, in comparison to the resistance of the same soil before freezing is another measure of frost action.

II. 111. Moisture Movement in Soils.

During Freezing.

Numerous reports by various individuals (1) have been presented regarding the presence of soft unfrozen clay between ice layers. This lowering of the freezing point in clay soils has been attributed to the "adsorption power" of the soil particles. Several investigators (1) have shown that the freezing temperatures of a portion of the adsorbed soil water is lower than that of free water, and that the finer grained the soil, and the lower the soil moisture content, the lower the temperature at which soils will freeze.

Taber (12, 13, 14) and Beskow (15) used the variation in

the freezing point of soil water to explain moisture movement and ice lensing during freezing. The free water in the largest voids freezes first and, as the temperature decreases, more and more adsorbed water is drawn to the growing crystal resulting in the development of an ice lense.

The significance of the lower freezing point in a clay soil is not that as subgrade materials they are less apt to freeze, but that the movement of water to the zone of ice crystallization is made possible by a depressed freezing point, without which ice lensing and heaving does not seem feasible. Further detrimental amounts of ice segregation depend on adequate water contained in the soil or available from a ground-water source near the freezing zone.

The effectiveness of vapour flow as a means of moving significant amounts of moisture to the freezing zone is a matter of some controversy. Beskow (15) showed that vapour diffusion could account for only about one thousandth of the rate of heave obtained in tests. More recently, Kuzmak and Sereda (16) on the basis of studies of moisture movement in a porous media showed that water migration due to suction gradients takes place in the liquid phase.

Following Thawing.

When the soil has thawed the increased water content seeks to redistribute itself in a manner to satisfy the forces which prevail. The water may be restrained from downward movement by the relatively impervious frozen soil beneath, or, on completion of thawing, by saturated soil beneath. In the latter case, reduction and redistrib-

ution of moisture to prefrozen condition must be accomplished by forces of gravity and evaporation. If no ground water source was available during freezing and all moisture gain above was at the expense of moisture loss below, the normal forces of soil suction will bring about redistribution.

The rate of redistribution is dependent upon 1.) the length of time during which it was moved upward by thermal forces due to below-freezing thermal gradients 2) the duration of the freezing period, and 3) the relative effect of all forces operative during freezing. It may be that the time for redistribution following thawing is proportional to 1) and 2) above. However, if the forces operative in moving moisture to the freezing zone are, as one investigator (14) holds, greatly in excess of the forces causing its redistribution, the redistribution may be a much slower process than was the period of active freezing.

II. 1V. Volume Change.
Swell (Heave).

The gain in moisture content associated with the freezing of most soils is associated with an increase in volume, which is spoken of as heaving if it occurs in visible amounts. The amount of segregated ice in a frozen soil system (number, thickness and distribution of visible layers or lenses) depends very much upon the intensity and rate of freezing.

Slow freezing produces ice lensing whereas quick freezing produces no visible lenses. Cyclic freezing and thawing produces ice segregation when the thawed ice waters freeze again. This also occurs when the

frozen soil thaws from the bottom and then the thawed section freezes again.

The process of formation of ice lenses by water movement within the soil by slow freezing has been outlined under Moisture Movement. The most prevalent theories regarding ice lensing and heaving are based upon this moisture movement to the frost line.

A rather unique theory regarding frost heaving was submitted by Schmid (19), who considered that the heaving was caused by air freed by the drop in temperatures. He stated "Experiment has shown that in the absence of such air, frost heaving does not occur. In soils containing colloids, frost causes alternate contraction and expansion of the colloids as the temperature falls and rises before and after the formation of ice. The place of water adsorbed in swelling is taken by air released from the moisture. If the air is not sufficient to fill all the space, shrinkage of the soil occurs with every fresh formation of ice, but if the air is more than sufficient, expansion results. Thus the degree of frost heaving depends primarily on the air content of the soil or soil moisture, and only secondarily on the moisture capacity of the soil on the ground water."

This theory has not been borne out by any other investigators and the wealth of data regarding ice lenses and their formation as the cause of heaving seems to indicate this theory is not valid. However, although the effect of air does not appear to be a major cause of heaving it could possibly be of some significance, especially in the case of closed systems and/or, partially saturated clay specimens.

Heaving in a Closed System.

A closed system infers that the water for ice segregation must come from that held within the soil.

Beskow (15) found that the resulting heave under closed system conditions is usually small, but that the freezing results in a marked increase in the water content in the frozen zone, causing a reduction in the load carrying capacity on thawing.

Taber (12, 13) froze a number of partially saturated clay specimens without access to free water, with freezing temperatures at the top of the specimens only. He found that segregated ice and heaving resulted and that there was a tendency for the moisture to become concentrated in the frozen upper part, even in the soils with the lowest moisture content.

Shrinkage on Freezing.

Shrinkage, associated with soil freezing may occur in different forms. Shrinkage below the zone of freezing may occur due to soil consolidation on removal of water as it is drawn to the freezing zone. Taber (12, 13) found that "in every experiment in which no additional water entered the system, the withdrawal of water from the lower part of the container to build up layers above, caused shrinkage in volume and, usually, the development of tensional cracks. This form of shrinkage is never seen in nature and has little significance beyond the appreciation that it reduces total heaving so that heaving is not directly proportional to the thickness of ice lenses obtained.

Shrinkage which results from freezing water-saturated well-compacted, heavy clay soils, is a second form of shrinkage that has far greater significance. This shrinkage manifests itself in the form of a marked downward movement of the soil surface and the development of large and often deep transverse cracks coincident with cracks or joints in overlying pavements.

Winterkorn in discussing this form of shrinkage states "it is common experience that the heavier the clay soils, the less in the effects of cooling to -10° F.; also in such cooling, water-saturated heavy clay soils, if initially well-compacted, are known to shrink with decreasing temperature, whereas intermediate soils expand under formation of ice". He explains this phenomenon with the aid of the phase diagram for water (Figure 1); and the concept that internal pressures may be assumed to produce the same type of results as external pressures.

The essential features of the phase diagram are noted in Table 1, and the following conclusions can be drawn from the diagram:

a) The melting point of water decreases with an increase in pressure only up to 2050 Kgm/cm^2 . At all higher pressures, the melting point increases with increasing pressure.

b) The maximum expansion pressure obtainable in the freezing of water is 2050 Kgm/cm^2 , and cooling below -22° C. does not increase the expansion pressure.

From the concept of equality of effect of external and internal pressures, may be added:

c) The liquid state is an unstable condition for water below -22° C.

and if water does not freeze under expansion at this temperature, this is because it is already solidified or is being solidified as a result of external or internal pressures as ice III, V or VI respectively.

Winterkorn determined the adsorption pressure for water of Florida fullers earth, that is, the adsorption forces between clay mineral surfaces and water, as equal to, if not considerably higher than 20,000 to 25,000 Kgm/cm², and indicates the adsorption pressures in clay soils are of comparable magnitude. He notes "The higher value obtained is especially significant because it represents an average pressure, since the pressure of adsorption is usually considered as falling off logarithmically with increasing distance of the adsorbed layers from the surface of the adsorbing solid".

Thus a high pressure form of ice is developed due to these high adsorption pressures, the volume of which is less than the volume of water, resulting in shrinkage of the soil mass. Winterkorn states, "The direction and amount of volume change occurring upon cooling below the normal freezing point of water depend not only upon the temperature reached and the total moisture content, but also upon the distribution of this moisture in the different ranges of adsorption pressures."

It appears that the adsorption pressure concept as demonstrated above may be profitably employed for the understanding of volume and stress phenomena occurring in water-cohesive soil systems above 0° C. Regarding this, Winterkorn states "The water adsorption capacity of soil colloids decreases with increasing temperature. Considering the melting point curve for ice VI, we may say that at increasing temperatures, soil water changes from ice VI into free water. This free water

FIGURE 1

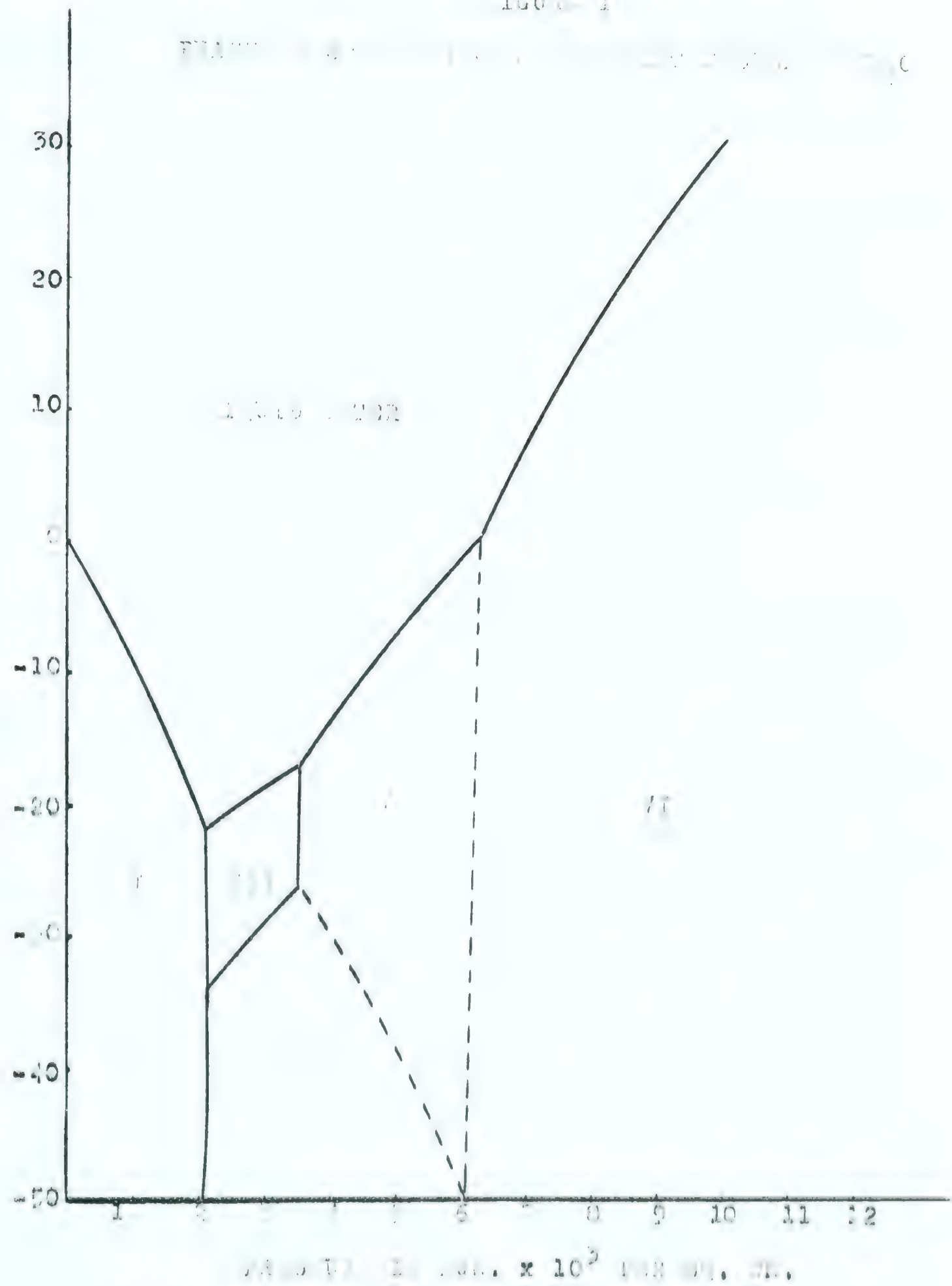


TABLE 1

TEMPERATURES AND PRESSURES IN THE TRIPLEPOINTS OF THE ONE-PHASE SYSTEM
WATER.

Phases in Equilibrium	Temperature	Pressures Kgm./sq. cm.
water--ice I--ice III	-22°C.	2050
ice II-- ice I-- ice III	-34.7°C.	2170
water--ice V-- ice III	-17.0°C.	3530
water---ice VI	0.16°C.	6380

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has a larger specific volume than ice VI and, if the permeability of the soil is too small to permit ready movement of the water, considerable expansive forces may be set up. The normal temperature fluctuations occurring in soils are, therefore, likely to produce a general decrease in the density of cohesive soils similar in effect, if not in magnitude, to that occurring as a consequence of the expansion resulting from the freezing of ice I".

II V. Resistance of Load Deformation.

Frost action has two opposite effects on the capacity of soils to carry loads. In the frozen state it provides a rigid structure which may develop very high load carrying capacity. But in an early thawed state, frost susceptible soils may lose a maximum of from 70 to 80 percent of the strength.

Recent investigations of load-carrying capacities of roads and airfields have been conducted (6, 10). The findings are significant and show a marked reduction in load carrying capacity of the average order of 40 to 50 percent of the fall season value.

Reduction in load carrying capacity is associated with a soil condition of increased moisture, decreased density and, possibly altered soil structure. Soils in which much water has accumulated and segregated into ice lenses during freezing will ordinarily undergo great reduction in load carrying capacity on thawing. However, observations (6, 2) have revealed that significant reductions may occur with relatively small water gain and little segregation on freezing. One purpose of this project is to determine to what extent cyclic freeze-thaw affects density and strength with no change in average moisture content.

Intensity and duration of the load reduction are largely dependent upon the rate and depth of freezing or thawing. Distribution of the ice within the frozen soil is critical. Rates of freezing which produce large segregations of ice near the surface and deep frost penetrations, in combination with early and rapid thawing to shallow depths produce the most unfavorable condition of excess moisture about a residual frozen layer.

II. VI. Structure of Frozen Soil.

Frozen soil assumes a structure which reflects the intensity of the processes of freezing and thawing on the inherent nature of the soil and its associated water conditions. Massive or homogeneous structure denotes soil water frozen in the soil pores and normally occurs in coarse-

grained soils, and in fine-grained soils of low moisture content, or those frozen at a rapid rate. Stratified or discontinuous-type structure contains visible ice segregation in lenses, wedges, veins, or needles and is usually associated with wet, fine-grained soils.

A photographic study (7) of the development of soil structure on freezing indicates variations in structure with soil type, and, in the case of clays, with clay minerals. In the case of homogeneous frost structure, practically no change in appearance as compared with unfrozen soil can be recognized macroscopically.

The stratified or heterogeneous frost structure occurs in markedly different forms depending on soil type, rate of freezing and water movement to the freezing zone. In clay specimens, polygonal structures are formed as a result of moisture loss and shrinkage of the clay which accompany the freezing process.

In montmorillonite, especially regular frost structures were found because of its large and uniform shrinkage. (7) A vertical section through a frozen montmorillonite specimen shows marked vertical ice layers and thin horizontal layers which extend over two vertical layers. A horizontal section through the same clay (parallel to the freezing plane) shows hexagons and pentagons in cell-like arrangements. Czeratzki and Frese (7) state "Aggregate formation in clayey soils as a result of frost action or of wetting and drying are related processes, since both are connected with swelling and shrinkage phenomena in the soil. This is why the resulting aggregate forms show great similarities and why, when both factors have acted on a soil, the specific cause can hardly be recognised."

CHAPTER III

TESTING PROGRAM.

III. 1. The Constituents.

Soil-

The soil used in this investigation was a highly plastic clay from a borrow pit ninety-five feet to the right of station 419#00, highway 2-G-3 located near the town of Fahler, Alberta, approximately 270 miles northwest of Edmonton.

After being received from the field the soil was mixed and air-dried, and at the beginning of this testing program had been stored in a dry room at normal temperatures for approximately five months.

An x-ray diffraction analysis performed by the Research Council of Alberta indicated that the soil contained illite as the principal clay mineral mixed with lesser equal amounts of kaolinite and montmorillonite.¹

According to the Unified Soil Classification System, the soil was classified as a highly plastic clay, (CH). Pertinent characteristics of this soil were:

Specific Gravity of Soil Solids	- 2.77
Liquid Limit - per cent	-67.6
Plastic Limit - per cent	-27.9
Plasticity Index - per cent	-39.7

The results of a grain-size analysis of the soil are as follows.²

-
1. Results as reported by Watt (1951).
 2. Results as reported by Brochu (1962).

MATERIAL	LIMITING DIAMETERS	PER CENT
Sand sizes	greater than 0.06 mm.	15%
Silt sizes	0.002 to 0.06 mm.	30%
Clay sizes	less than 0.002 mm.	55%

Water-

Distilled water was used throughout the program to eliminate any variations that might result from impurities added with ordinary tap water.

III. 2. Scope of Testing Program.

This program was divided into three portions. The aim of each portion was the same in that the effects of cyclic freezing and thawing at constant moisture content on volume change and strength of compacted specimens was investigated. The variables in each portion of the program were the compactive effort and/or the moisture content at compaction.

One series of tests was conducted on specimens compacted with a compactive effort designed to give standard Proctor density, and at a moisture content which was optimum for this compactive effort. A second series of specimens was compacted using the same compactive effort, but at a moisture content approximately 4% above the optimum value. The third group was compacted using a compactive effort designed to give modified Proctor density, and at a moisture content which was optimum for this compactive effort.

The specimens formed were cylindrical in shape and measured 2

inches in diameter by 4 inches in length. The compaction used to simulate standard Proctor compaction was accomplished by compacting the specimens in four equal layers using ten blows per layer of the standard compaction hammer (5.5 lb. and 12" drop.) Optimum moisture content for this compactive effort was 26%.

Modified Proctor compaction was simulated using four equal layers and fifteen blows per layer of the standard compactive hammer. The optimum moisture content for this compactive effort was 22%.

The program was organized so that one half the specimens in each group were subjected to freeze-thaw and the remaining half remained in the moisture room with no variation in conditions. At any time during the testing program when a number of specimens which had been subjected to freeze-thaw were tested, a similar number of the "stand-by" specimens were tested.

In each group fifty-four specimens were compacted. One week after compaction six specimens were tested in triaxial compression. Twenty-four of the remaining forty-eight specimens were subjected to freeze-thaw, and twenty-four were placed in the moist room for storing.

The specimens were tested in triaxial compression in groups of twelve, six from each portion, after one, three, nine and fifteen cycles of freeze-thaw. Also, length and volume measurements were made on the samples subjected to freeze-thaw after each cycle.

The results obtained from the program include the variation of length and volume change with cycles of freezing and thawing; the variation in compressive strength with cyclic freeze-thaw, and the dry density, moisture content, void ratio and degree of saturation of each specimen at failure. In the case of the specimens which remained in the

moisture room the variation in compressive strength with time is included.

III. 111. Testing Procedure.

Mixing-

The soil, in the air dry state, was in large, hard clods. These were broken down by a mechanical jaw crusher and a pulverizer until the majority of the material would pass the #40 sieve. No exact particle size was aimed at, but the mechanical grinder was set, and the entire quantity of soil passed through at the one setting, assuring similarity of particle size. The pulverized soil was then mixed and stored in plastic bags until needed. The hygroscopic moisture content of the air dry soil was determined and found to be 3%.

A sufficient amount of air dry soil for each group of specimens was weighed out, allowing a quantity for wastage due to trimming specimens and possible breaking of samples, and for determining moisture contents. The required amount of distilled water necessary to bring the moisture content to that desired for compaction was added by a spray bottle and the moist soil was mixed by hand in a large tray. Approximately thirty minutes was required for addition of the water and mixing, until by visual inspection the moisture was reasonably uniformly dispersed and no large lumps of moist soil existed. Following this the soil was placed in two plastic bags, tightly closed, and allowed to sit in the moist room for four days before compaction to allow further distribution of the moisture.

The final moisture content for each group of specimens was as

follows-

GROUP 1 - $26\% \pm 0.5\%$

GROUP 2 - $30\% \pm 0.5\%$

GROUP 3 - $22\% \pm 0.5\%$

Compaction-

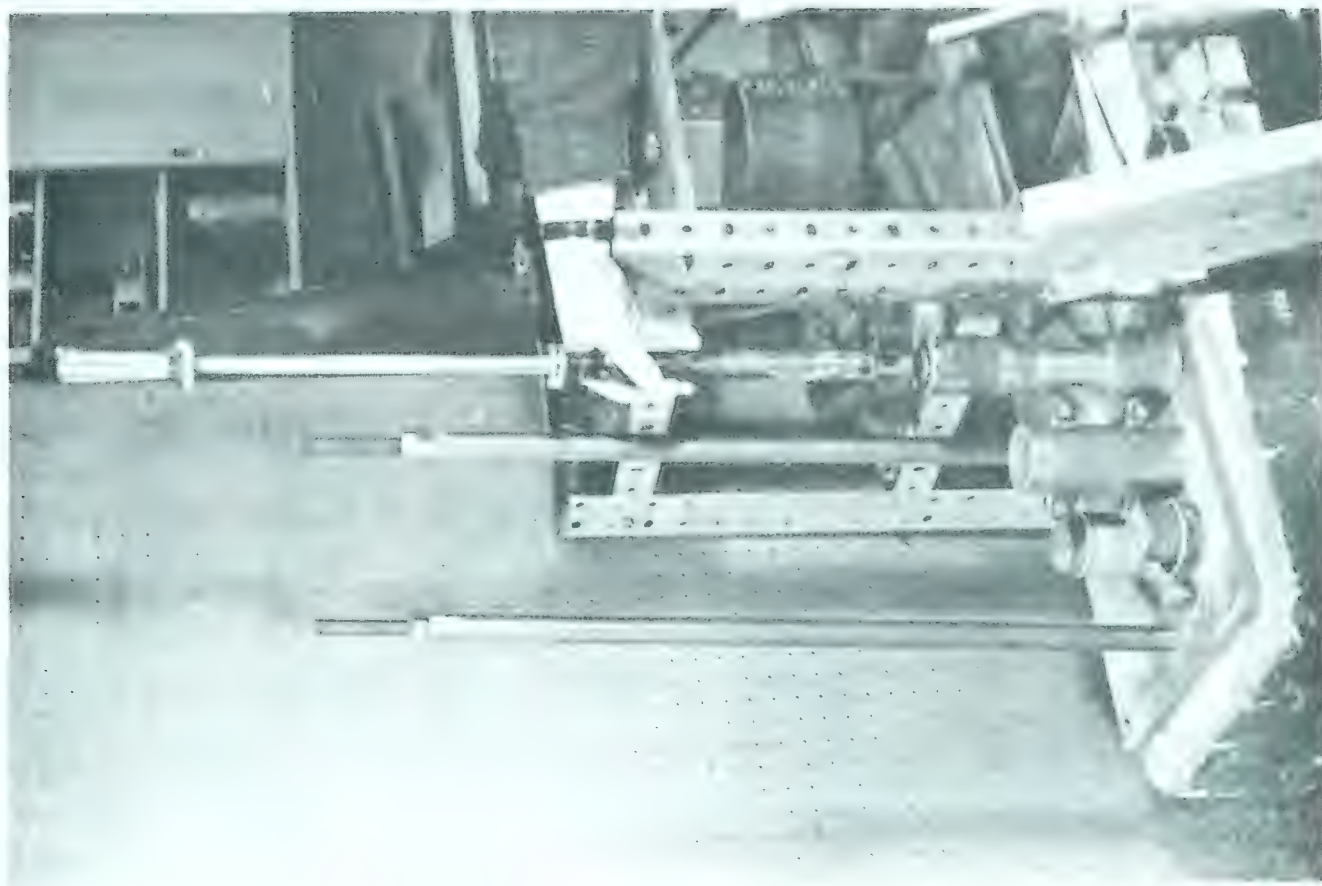
One group of specimens was compacted at one time and required six to seven hours work for two technicians. Fifty-four 2 inches by 4 inches cylindrical specimens were compacted for each group by compacting the specimens in four equal layers with a compactive effort of 10 blows per layer, for Groups 1 and 2, and 15 blows per layer, for Group 3, of the standard compaction hammer (5.5 lb. and 12 in. drop) using the apparatus shown in Figure II. The extrusions of the specimens from the mold was accomplished by means of the hydraulic apparatus portrayed in Figure II.

Initial Measurements and Treatment.

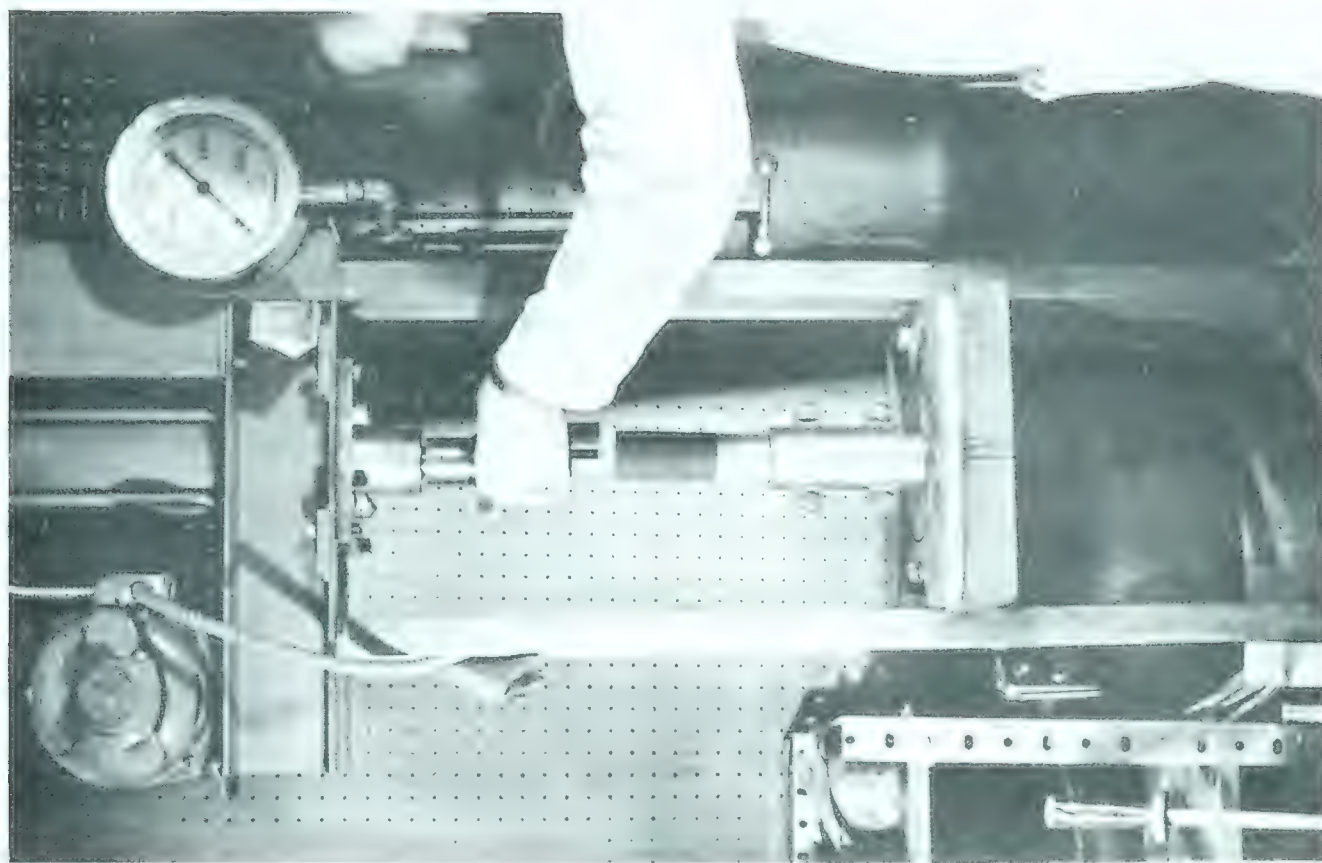
A specimen, removed from the mold, was weighed to the nearest 0.1 grams, and following this the length of the specimen was measured to the nearest 0.001 inches. This length measurement was made by means of calipers and was the average of two measurements, at right angles to each other.

Immediately following the length measurement a specimen was taken into the moisture room to be coated, to insure a constant moisture content was attained. The material used for coating was a rubber latex material which dried in air from a slightly viscous liquid to a stretchy

FIGURE II



COMPACTION EQUIPMENT AND MOLD



EXTRUDING SPECIMEN FROM MOLD

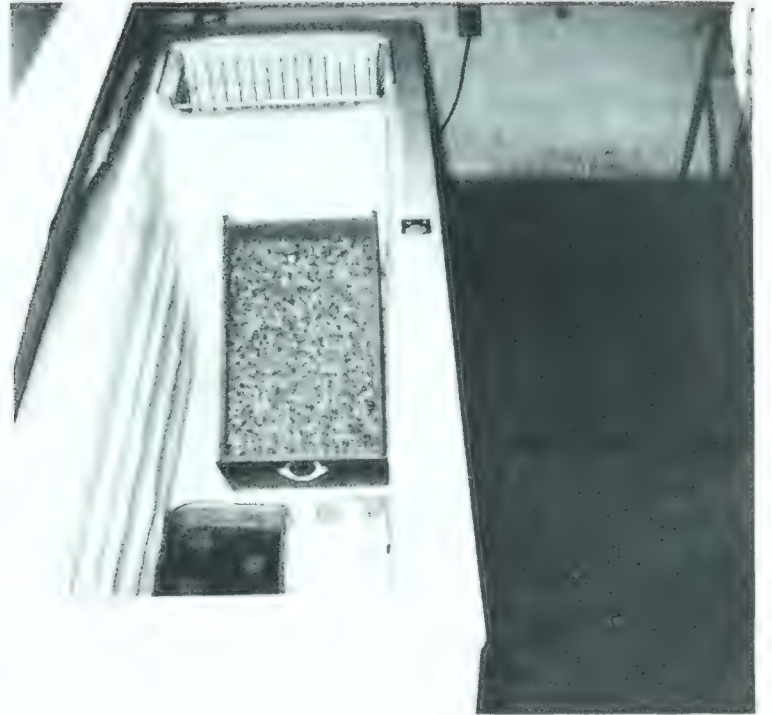
rubber-like solid. This material was sold under the trade name Duncoat 101 by Continental Rubber Company.

A specimen was held by a pair of tongs and completely submerged in the liquid assuring a complete coating, and after a short period to allow the excess latex to drip off, the coated specimen was set on end on a greased surface. The greased surface was used since it was found that the latex would not stick to a greased surface and thus the specimens could be easily removed after curing of the coating. A curing period of about eight hours was required for the latex before the specimens could be handled and thus the entire group of specimens were allowed to sit in the moisture room until the next day.

After curing of the latex the specimens were removed from the greased surface and excess latex was removed from around the bottom of the specimens (i.e. latex which had formed a pool around the specimen before hardening). A small area of latex covering about one inch in diameter was cut away from the centre of one end of each specimen with a sharp knife, exposing the specimen. The surface of the specimen was scarified using a small nail and a demigage point was glued to this surface, (Figure III) using a patent glue. (Lepages)

This glue required a period of about two to three hours to harden, after which that end of the specimens were dipped in latex to roughly one-half height and were set to cure on the other end. After a suitable curing period of about eight hours a demigage point was added to the other end of the specimen in a similar manner, and that end of the specimen dipped, thus applying a double coating of latex to the entire surface of the specimen. A third coating was applied the following day

FIGURE III

SPECIMEN SHOWING COMPACTION
PLANES AND LATEX COVERING

SPECIMENS IN DEEP-FREEZE



LENGTH MEASURING EQUIPMENT



VOLUME MEASURING EQUIPMENT

(i.e. the third day after compaction) by the method of alternately dipping the ends. These coatings effectively prevented any loss of moisture from the specimens during subsequent treatments. This was borne out by the small variation in moisture content between specimens tested at 0 cycles (i.e. as compacted) and specimens tested at 15 cycles.

One week after compaction the twenty-four specimens were divided as follows - six specimens for strength testing that day, twenty-four as "stand-by" specimens and placed in the moist room, and twenty-four specimens for the freeze-thaw treatment. The method of selecting specimens was as follows: Numbers 1, 10, 19, 28, 37, and 46 comprised the initial group of six; the remaining twenty-four even numbers comprised the "stand-by" specimens. These groups of twenty-four specimens were divided into four groups of six with one specimen numerically lying between each of the initial six specimens (i.e. 1 group would be 2, 12, 20, 30, 38, 48).

Length and Volume Measurements.

Length and volume measurements were made only on the specimens subjected to freeze-thaw. Length measurements were made using the demigage points and the Ames dial set-up shown in Figure III.

Volume measurements were based on the principle of bouyancy (i.e. that the weight of an object is decreased when submerged in a liquid by the amount of liquid it displaces.) To determine the volume, the specimens were weighed in air to the nearest 0.1 grams, and then weighed, while suspended in water, to the nearest 0.1 grams. (see Figure III)

Freeze-Thaw Cycling of Specimens.

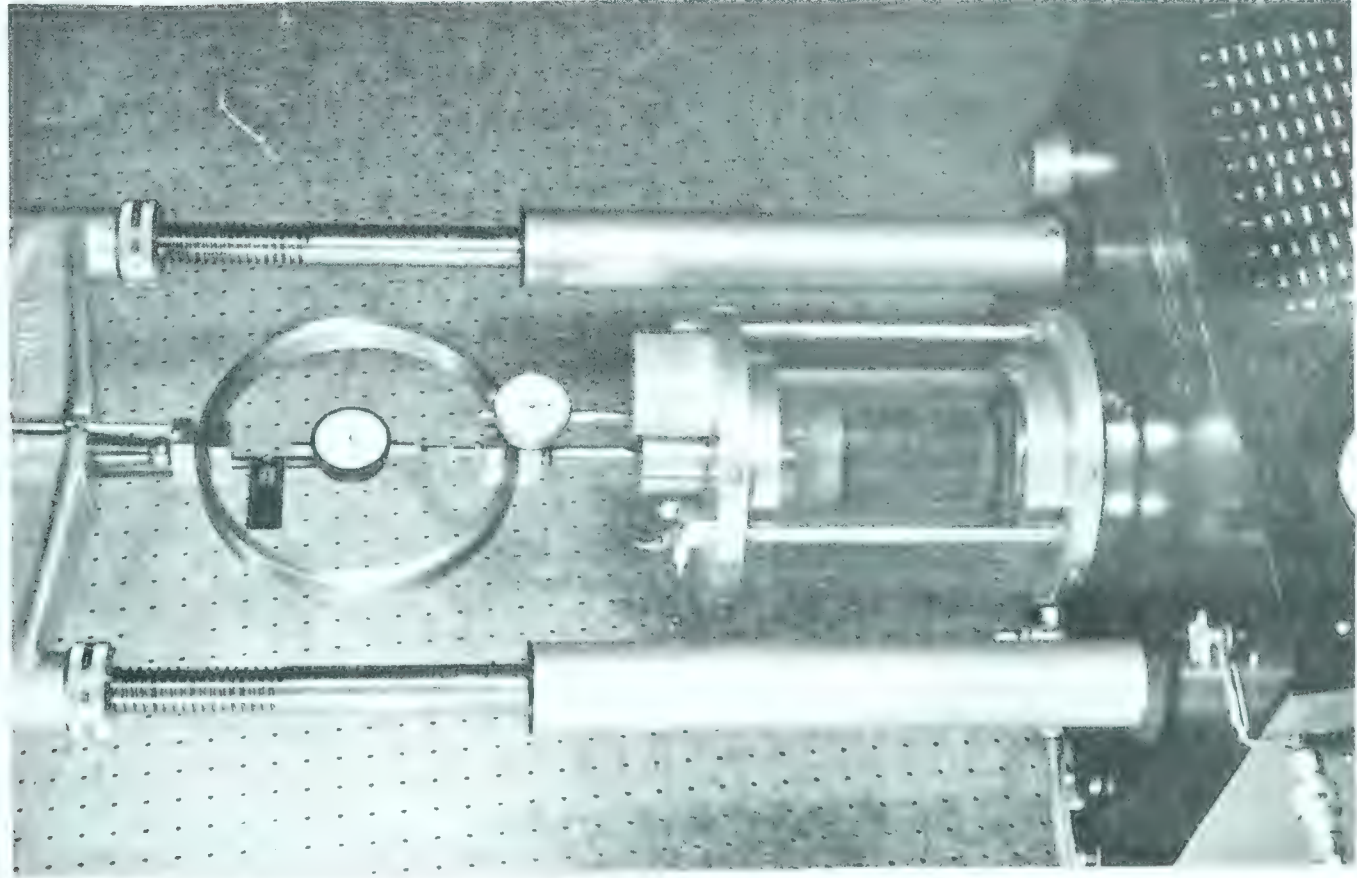
Following the determination of the original length and volume of the specimens, they were placed in a deep-freeze maintained at 0°F . Investigation showed that from five to six hours were required to completely freeze the specimens at this temperature, and that a frozen specimen required approximately the same amount of time to become completely thawed at normal room temperatures- (approximately 70°F .) Thus it was possible to complete one cycle of freeze-thaw per day by removing the specimens from the deep-freeze in the morning, and returning them in late afternoon such that the time out of the deep-freeze varied little from eight hours.

Length and volume measurements were made on each specimen immediately upon removal from the deep-freeze, i. e. when completely frozen, and before returning to freezing temperatures, i.e. completely thawed. Following each of 1, 3, 9, and 15 cycles of freeze-thaw six specimens were tested in triaxial compression. Since a full day was required for breaking six specimens, it was necessary to remove the specimens from freezing the evening before testing and allow them to thaw overnight. Final length and volume measurements were then made on the specimens the following morning before testing.

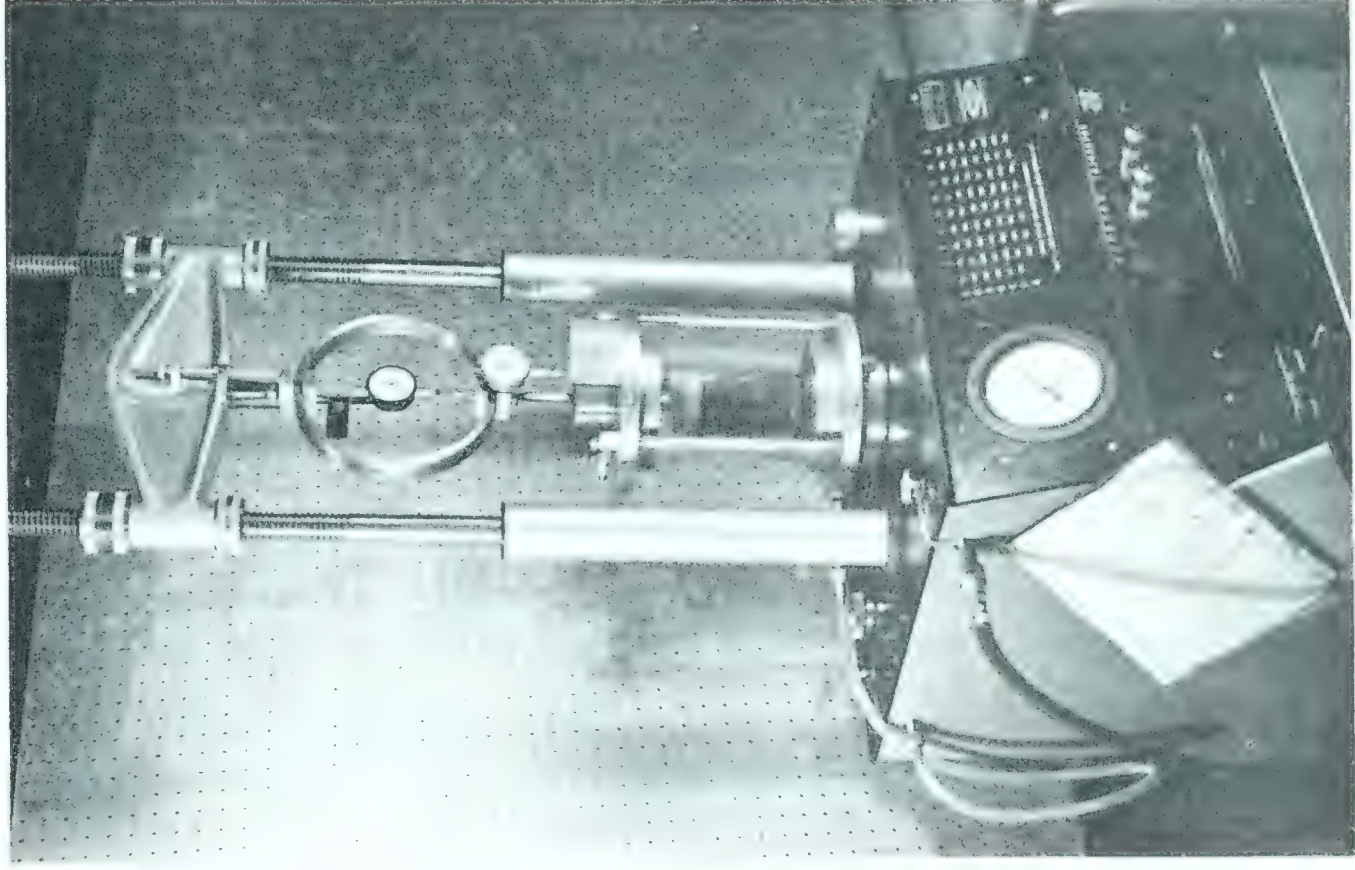
Triaxial Compression Test.

The specimens were tested in triaxial compression using a standard triaxial cell and a Leonard Farnell Compression Machine. (Figure 1V). The method of testing was the so-called "quick" test in which

FIGURE IV



SPECIMEN IN TRIAXIAL CELL



TRIAXIAL TEST IN PROGRESS

the load is applied to the specimens immediately after the application of the lateral or all-round pressure, with no drainage allowed either before, or during loading to failure. Lateral pressure was applied to the water in the cell through a connection to a "water over air" system, in which the pressure was supplied by the air pressure from a laboratory outlet, and manually controlled by an air pressure gage.

Each of the six specimens in a group was tested at a different lateral pressure, these pressures being 0, 15, 30, 45, 60, and 75 lb./in.² The rate of strain used was 0.010 in./min. Load applied to the specimen was determined by recording strain in the proving ring, the frequency of these readings being governed by the strain of the specimen (i.e. based on specimen length of 4", readings were taken at a specimen strain of .1%, .2%, .3%, .4%, .6%, .8%, 1.0% and then every .4% until failure). The criterion for failure was taken as the maximum deviator stress applied to the specimen, but loading was usually continued until the proving ring dial readings began to decrease.

The maximum load applied to a specimen was determined from proving ring calibration curves, and the area at failure was calculated from the specimen strain at this load. Two proving rings were used in the program, depending upon the relative strength of the specimens. Proving ring No. 1873 with a capacity (nominal) of 1600 lbs. was used for Group I and III; proving ring No. 1872 with a nominal capacity of 400 lbs. was used for Group II.

Specimen Preparation For Triaxial Testing.

The loading head of the triaxial cell could not be placed

directly on the specimen since the demigage points would cause stress concentration in the specimen. Initially, this was overcome by the addition of sulphur caps to the ends of the specimens and then applying the load through these caps. When this method was used the latex coating acted as a membrane.

This loading method was used for Group I and then discarded because the sulphur caps cracked and thus some of the strain recorded was due to the caps cracking and not in the specimen. Also, since it was difficult to form the caps normal to the long axis of the specimen some eccentricity in loading was encountered, and it was possible that the edges of the caps, which extended down the sides of the specimens approximately $\frac{1}{4}$ " had some effects on the end restraint and l/r ratio of the specimens.

For Groups II and III, the latex covering was cut away from the specimen ends and the glue and demigage points were stripped off. The cell loading head was then set directly on the specimen, over the portion of the latex membrane remaining.

After failure, the remaining latex covering was removed and the entire specimen used for determining the moisture content. It was necessary to scrape some of the soil from the latex covering in order to get all the soil, especially as the number of cycles of freeze-thaw increased.

Additional Tests

Following completion of a major portion of the original testing program, additional minor tests were devised in an attempt to clarify

the results which were being obtained.

Consolidation Test.

A consolidation test was run on a portion of a specimen to provide additional information about the compacted soil, which could possibly help explain the erratic results of the triaxial tests at high lateral pressures. To accomplish this, a special consolidation ring, 2" in diameter by 1" in height was made, which provided a snug fit for a specimen. A porous stone and a loading head were also made such that they would fit inside the consolidation ring with a fairly close tolerance.

A specimen was then formed using mixing and compaction procedures as outlined previously in this chapter. The specimen was fitted into the consolidation ring and a portion of the specimen near the middle of the 4" length selected for the test. A considerable amount of pressure was required to force the specimen into the consolidation ring indicating little room for lateral swelling of the sample.

The general procedures followed in running this consolidation test are essentially those outlined on page 78 of reference number 22. A conventional consolidation machine was used, and the sample was allowed to swell freely at the beginning of the test.

Additional Freezing Tests.

In an attempt to determine if there was any moisture migration in the compacted specimens during freezing, an additional group of specimens were formed and subjected to directional freezing.

Fourteen specimens were compacted using the same mixing and compaction procedures as outlined previously in this chapter. The specimens were then covered with latex in the manner previously described, with the exception that demigage points were not glued to the specimens.

Two specimens were selected for determining moisture contents at 0 freezing cycles, or previous to freezing, and the remaining twelve specimens were divided into two groups of six. One group was frozen by simply placing them in the deep freeze so that they would freeze from every direction at once. (i.e. in the same manner as the specimens in the original testing program). The second group was in the box of insulating material (zonolite) such that only the tops were visible, and this box containing the specimens was placed in the deep freeze (see Figure 111). Thus the freezing temperature should have penetrated into these specimens from the top. Moisture contents of various portions of the specimens were determined at 0, 1, 2, 3, 5, 7, and 9 cycles of freeze-thaw, using one specimen from each group.

For the group of specimens subjected to "all-round freezing", moisture contents were determined separately for the top one-half inches of the specimen, the bottom one-half inches, a roughly circular strip one-third to one-half an inch around the outside of the specimens and for the remaining central core. Moisture contents for the group of specimens subjected to "end" freezing, were made on each of eight roughly equal portions, obtained by cutting the specimens at right angles to the height into eight similar sections. The

specimens were cut in the frozen state, with the exception of the two at 0 cycles, to insure that if moisture did migrate upon freezing, it did not have an opportunity to re-orient itself upon thawing..

III. IV. Discussion of Procedures.

Compaction.

The compactive method used (i.e. four layers and ten blows of 5.5 lb. hammer) was originally adapted by the Research Council of Alberta for obtaining standard Proctor density on 2" diameter by 4" length specimens for sands at optimum moisture content. In an attempt to determine the compaction necessary to give the optimum density for the moisture content used, (i.e. Group 1 - $W = 26\%$) test samples were compacted using four layers and each of 8, 9, 10, 11, and 12 blows per layer of the standard hammer. The variation in density was slight over this range of blows and, in fact, varied little from the normal variation in density that could be encountered in a group of specimens using the same number blows for each specimen. Since a comparative effort of 4 layers and 10 blows per layer had been used by Brochu (18) to approximate standard Proctor density for the same soil with additives: and since a quantity of soil necessary to determine the actual standard Proctor conditions of optimum moisture and density was not available, it was decided to use the compactive method of 4 layers and 10 blows per layer for standard Proctor compaction. The moisture content used for Group I was the standard optimum moisture content², and it was assumed that the density obtained by the compactive method used would be fairly close to the standard Proctor

density.

In actual fact, the dry densities obtained were higher (5 or 6 lbs./ft.³) than the dry densities determined by the standard method, i.e. using a 4" mold and standard Proctor compaction.³ This is possibly due to compaction from both ends, and/or to the static compaction effect produced by extruding the sample from the mold.

In a manner similar to that outlined above, the compactive effort for modified optimum density was established at modified optimum moisture content. The modified dry densities obtained were slightly lower (2 to 3 lbs./ft.³) than dry densities produced by the standard modified method.³ This could be due to side effects of the smaller 2" diameter mold (compare to the standard 4" diameter mold), and possibly to a moisture content of some specimens which is up to 1.5% above the optimum value. The variations which occurred from the actual standard and modified densities indicates that the respective compaction method used should possibly be revised.

The method of compaction used i.e. four layers with compaction from both ends, and extruding the specimens by applying pressure on the bottom produced a variation in density throughout the specimen length. The decrease in density from bottom to top of the specimen was easily visible with pore spaces visible in the upper layers. To reduce any effects this variation might have had on specimen strength all specimens were tested with load applied on the upper end as compacted.

3. As determined by The Research Council of Alberta.

Moisture contents were taken from the uncompacted soil at intervals during the compactive process to determine the moisture content at compaction.

Moisture Proofing.

The use of rubber latex to maintain moisture content was successful and the moisture content of the specimens varies less than 0.5% over a period of one month. One disadvantage of its use, however, is the length of time required to apply three coatings, which in this program, was made more difficult by the addition of the demigage points. The development of a more rapid means of applying the latex would make this method both effective and efficient.

It was found that the specimens lost from 1 to 2% in moisture content during compaction and addition of demigage points and latex. This was based on the difference in average moisture contents of the soil taken during compaction and of the specimen at failure.

Length and Volume Measurements.

The method of measuring length variation was accurate for specimens in the frozen state. For the thawed specimens some length decrease was encountered when measuring length since the entire weight of the specimen was bearing on the small demigage points, forcing them into the specimen. This was noticeable for Group II where the moisture content was quite high and the specimens were somewhat soft.

Volume change measurements were less accurate than length measurements since it was possible that specimen volume changes were not

reflected through the latex coatings. This was especially noticeable for Group III where bulges in the coating, which seemed to be caused by compressed air, were evident when the specimens were in the frozen state. One other factor which led to inaccuracies in volume measurements, was moisture condensation of the frozen specimens both during freezing and when taken from the deep freeze, which would affect the specimen weight.

However, since the volume change results used were the average of all the specimens measured at any one time, any error in one or two specimens due to the above would not be too significant in the final average.

Freezing and Thawing.

One cycle of freeze-thaw was completed during one day. If it was necessary to miss a day between cycles, the specimens were left in the frozen state for that period and it was assumed that conditions within the specimen would not change while frozen.

The length of time that the specimens remained out of freezing was constant at approximately eight hours, since early investigations showed that length and volume change varied with time in the thawed state.

The temperature for freezing was set at 0.⁰ F. to represent more or less an average of winter temperatures rather than an extreme, and since it was found that at this temperature one cycle of freeze-thaw could be completed in one day. Actual average ground temperatures in nature would be above zero degrees Fahrenheit.

"Stand-By" Specimens.

Originally the purpose of these specimens was to insure that the expected strength loss was due to freeze-thaw effects and not due to the time element between compaction and testing. When first tests indicated an increase in strength in these stand-by specimens with time, it was decided to continue this portion of the tests.

Triaxial Testing of Specimens.

When the testing program was set up it was decided to use the "quick" test at varying confining pressures for strength testing rather than unconfined tests, in an attempt to determine whether freeze-thaw affected the cohesion or angle of internal friction of the compacted soil, and to what extent. The testing method was only partially successful towards this end, since erratic results at some confining pressures prevented accurate plotting of the Mohr envelope on the Mohr diagram, and thus prevented accurate determinations of the cohesion and the angle of internal friction.

Possible the major drawback to an accurate evaluation of the cohesion and angle of internal friction was that only total stresses and not effective stresses were determined from the triaxial tests. Since the determination of effective stresses necessitated pore pressure measurements, which would have to be both water and air pore pressures since the specimens were only partially saturated, no attempt was made at determining these pressures as the necessary equipment was not available.

Also, the time required for running a single triaxial test (i.e. six per day) limited the number of specimens that could be used

in the testing program, and for this reason, each result is the result of a single test rather than an average. Thus, a possible erratic result must be accepted and the reliability of some strength values is, therefore, open to question.

Comparison tests run to determine if the method of testing using sulphur caps produced results different from those by the conventional triaxial method showed a slight scattering of values that indicated no trend and that were a "within specimen" variation. The latex covering provided a suitable membrane and the only incidence of leaking occurred at higher pressures after the specimens had been handled considerably (i.e. at 9 or 15 cycles), indicating the leaks probably occurred at spots weakened by this handling.

An inability to orient the plane of the caps at right angles to the specimen length caused eccentricity of loading and some buckling on specimens which were especially poorly centered. This did not appear to affect the total axial load greatly, but resulted in an increase in specimen strain.

The majority of all specimens tested exhibited shear failure with the remainder failing by bulging. Bulging failures occurred mainly in specimens which had been subjected to a number of cycles and were at higher moisture contents (i.e. Group II). This type of failure exhibited a greater amount of strain than did the shear failures.

Shear failures were mainly of the cup-cone variety and generally occurred at both ends of each specimen, with the edge of the cone starting directly below, or above, the edge of the loading head. Moisture contents were taken along the shear failure in some specimens but no difference in moisture content was encountered between the

shear zone and the remainder of the specimens.

CHAPTER IV.

DISCUSSION OF RESULTS OF VOLUME CHANGE CHARACTERISTICS.

Dry Density.

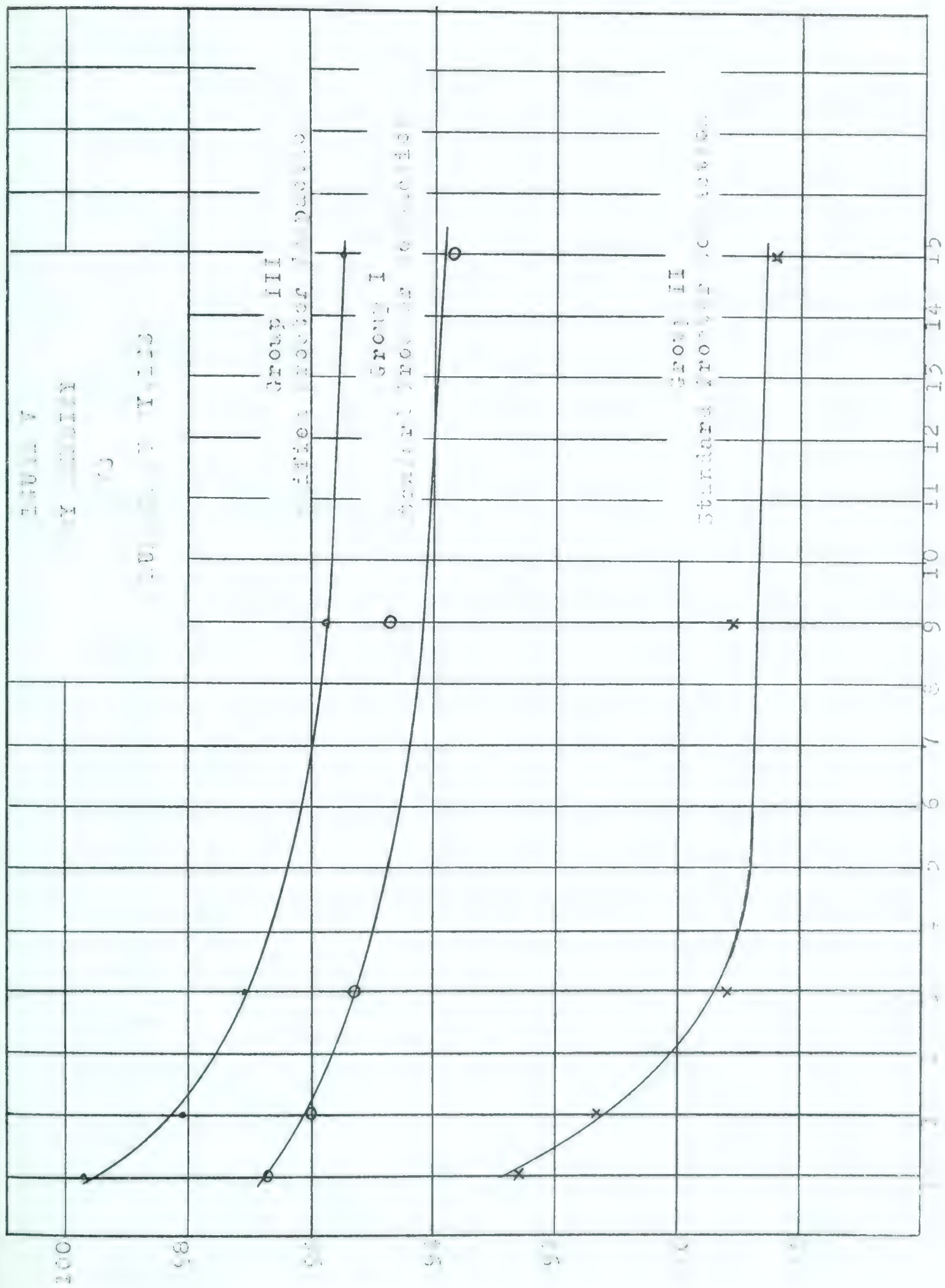
The effect of cyclic freeze-thaw on the dry density of the compacted specimens is shown graphically on Figure V. All three groups show the greatest portion of total loss in density in the first few cycles of freeze-thaw, after which there is very little further loss. This is especially true for the high moisture content specimens (Group II) which show virtually all the density loss in the first three cycles. The density values plotted are values for the specimens in the thawed state. Based on original dry density, the total percent loss in density at fifteen cycles of freeze-thaw for each group is listed in Table II, along with other pertinent data.

These limited results indicate that standard Proctor compaction at optimum moisture content are the conditions at which this clay exhibits the smallest loss in density due to freeze-thaw cycling, and if minimum loss in density were the governing factor, this compaction would appear to be best for this material. The increased percent loss in density for the specimens at modified Proctor compaction, indicates moisture content is not the governing factor for density loss, and that this amount of increased compaction cannot eliminate frost effects.

EFFECTS OF CYCLIC FREEZE-THAW.

TABLE II

Group	Compaction	Original				Maximum		
		w %	δ_d $\frac{lb}{ft^3}$	e	S %	Percent Loss		
I	Standard Proctor at Optimum Moisture	26.0	96.7	.782	82.9	δ_d	e	S
						3.11	5.1	2 3
II	Standard Proctor at 4% Above Optimum Moisture	30.0	92.6	.868	91.6	4.54	10.5	7 7
III	Modified Proctor at Optimum Moisture	22.0	99.7	.739	80.6	4 21	9.7	8.2



GROUP I

GROUP II

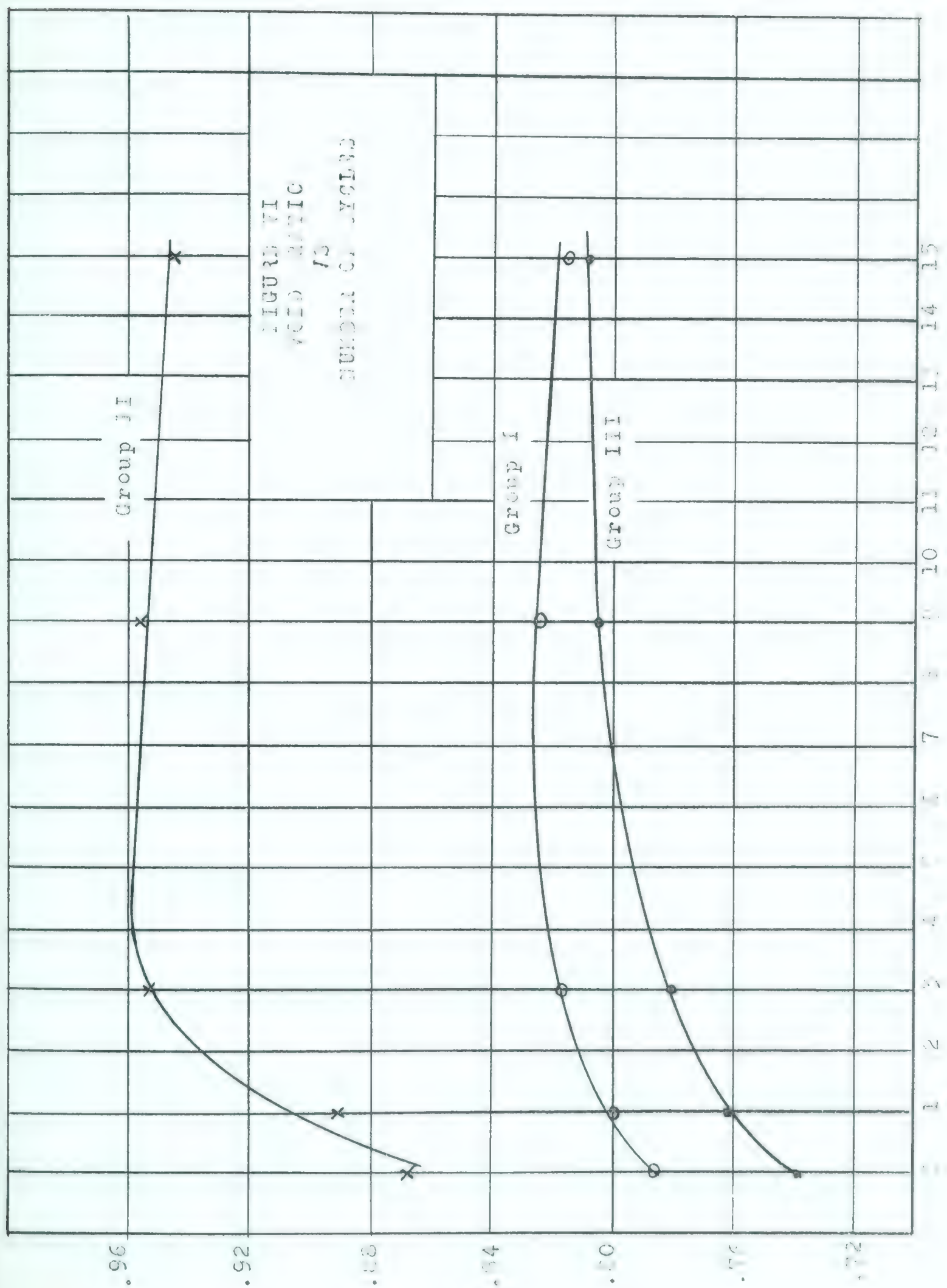
GROUP III

Void Ratio

The plot of void ratio versus number of cycles (Figure VI), is virtually an exact reversal of the plot of dry density versus cycles. Groups I and III show a fairly gradual increase in void ratio but Group II shows a marked increase up to three cycles of free-thaw, followed by a levelling off and finally a slight decrease is indicated. Based on original void ratio the maximum increase in void ratio is as shown in Table II.

Degree of Saturation

The plots of degree of saturation versus number of cycles (Figure VII) is similar to Figures V and VI, showing the majority of change within the first three cycles, with the exception of Group III which shows a very gradual decrease in degree of saturation. Group I has a small total decrease in degree of saturation and shows an increase at fifteen cycles over nine cycles. This increase is probably caused by the combination of the slight decrease in void ratio evident in Figure VI and a slight increase in moisture content. The increase in moisture content could be caused by one or more of three factors: (1) an increase in moisture content from an outside source, (2) an increase due to "freeing" of water from clay particles caused by freezing, or (3) a possible variation in original water content from the specimens at nine cycles. Of these factors the third appears to be the most obvious cause. Little opportunity existed for the samples to pick up outside water and, in fact, there would more likely be a decrease in moisture content if the membrane did leak. The second factor is a possible cause



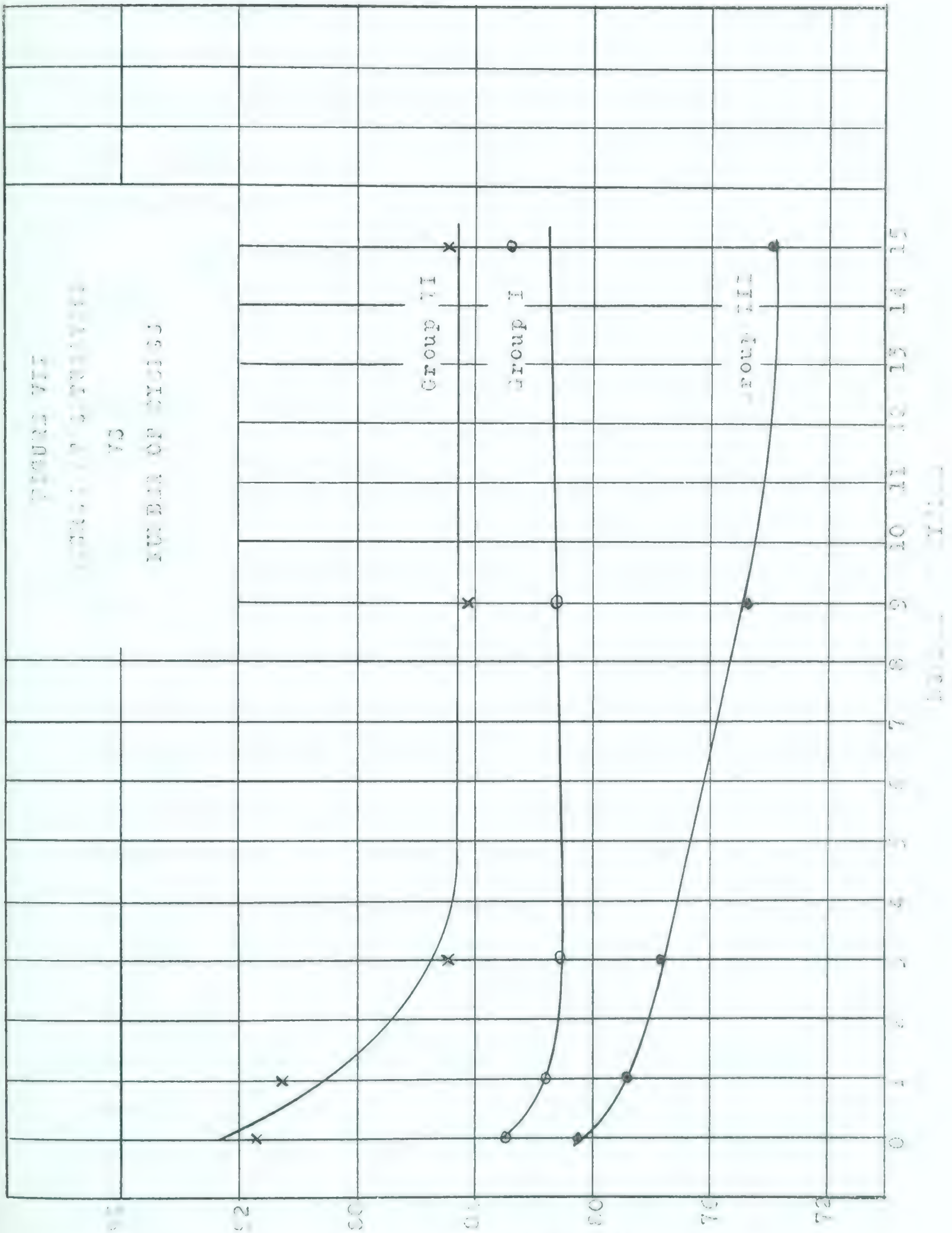
501223-20-2755-54

FIGURE VII

GROUP I, II, III

VS

NUMBER OF CYCLES



but it is unlikely that this type of change should occur after nine cycles and that the apparent increase which occurred (approximately 0.5 to 1% moisture) could be attributed to "freeing" of water molecules. Further, if this "freeing" of water does happen it should also appear for Groups II and III, and this is not evident.

The maximum percent decreases in degree of saturation are shown in Table II.

Volume and Length Change.

Volume Change.

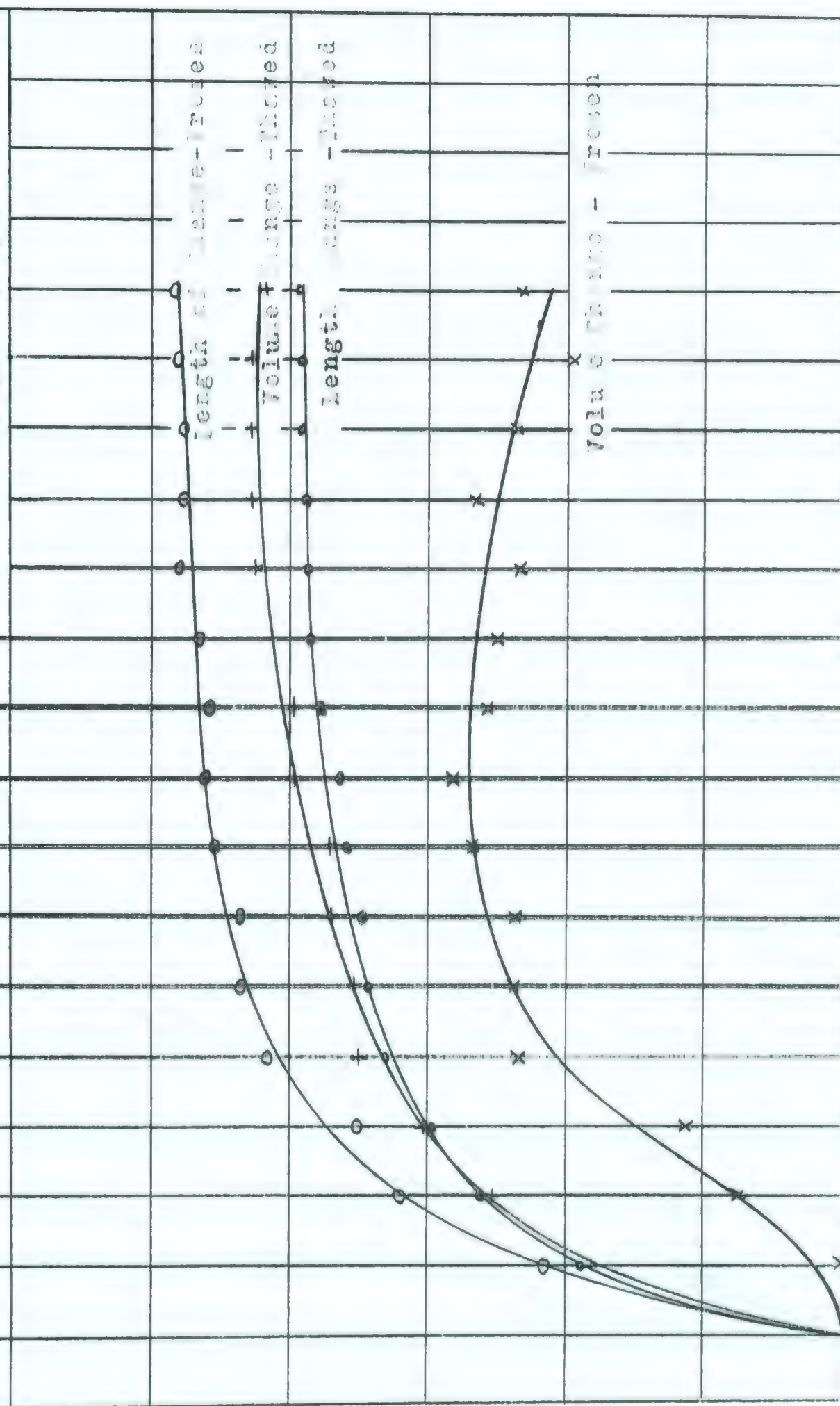
Volume and length variations with freezing are shown in Figures VIII, IX and X for Groups I, II and III, respectively. The pertinent relationships with regard to volume change, considering all three groups are: (1) The volume of Groups I and II, in the frozen state, increase with cycles up to nine or ten cycles and then decrease slightly. Maximum volume changes are Group I = 1.35% and Group II = 6.3% over the original unfrozen volume. (2) The frozen volumes of Group III decrease abruptly 2.5% at one cycle from their original volumes, and then gradually increase with cycles, appearing to level off at a volume decrease of 0.75%. (3) The thawed volume curves roughly parallel the frozen volume curves, with Groups I and III showing a higher thawed volume than frozen volume and Group II showing the reverse. All thawed volume changes are positive and only Group II shows a slight tendency toward a decrease in thawed volume at fifteen cycles. Maximum percent thawed volume increases over original volumes are Group I = 2.15%, Group II = 5.1%, Group III = 3.7%.

FIGURE VIII

GROUP I

STRETCH AND VOLUME CHANGES
VS

NUMBER OF CYCLES



11-10-50 22-11-50

FIGURE II
 GROUP II
 LENGTH AND VOLUME CHANGE VS.
 NUMBER OF HOURS

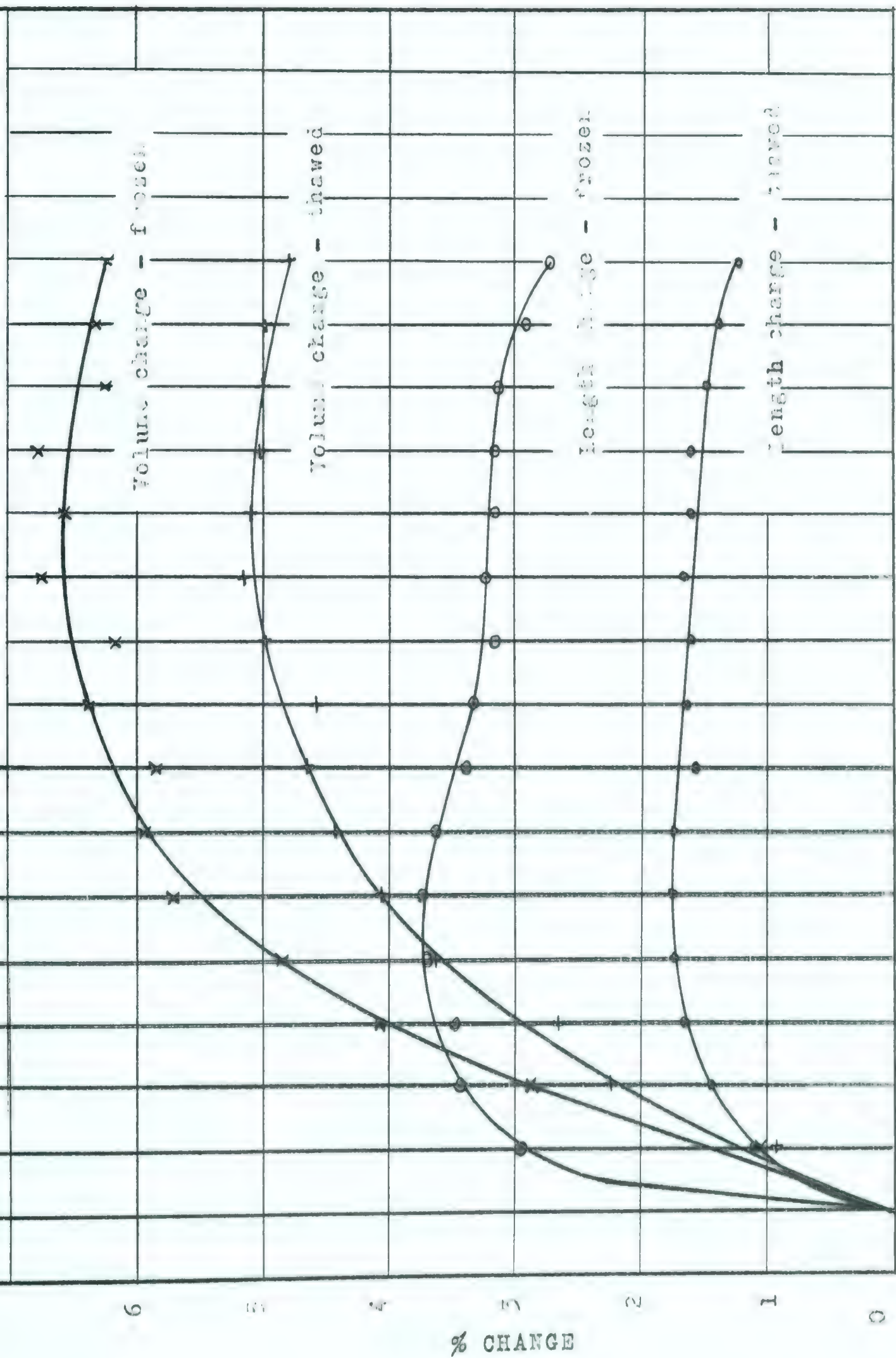


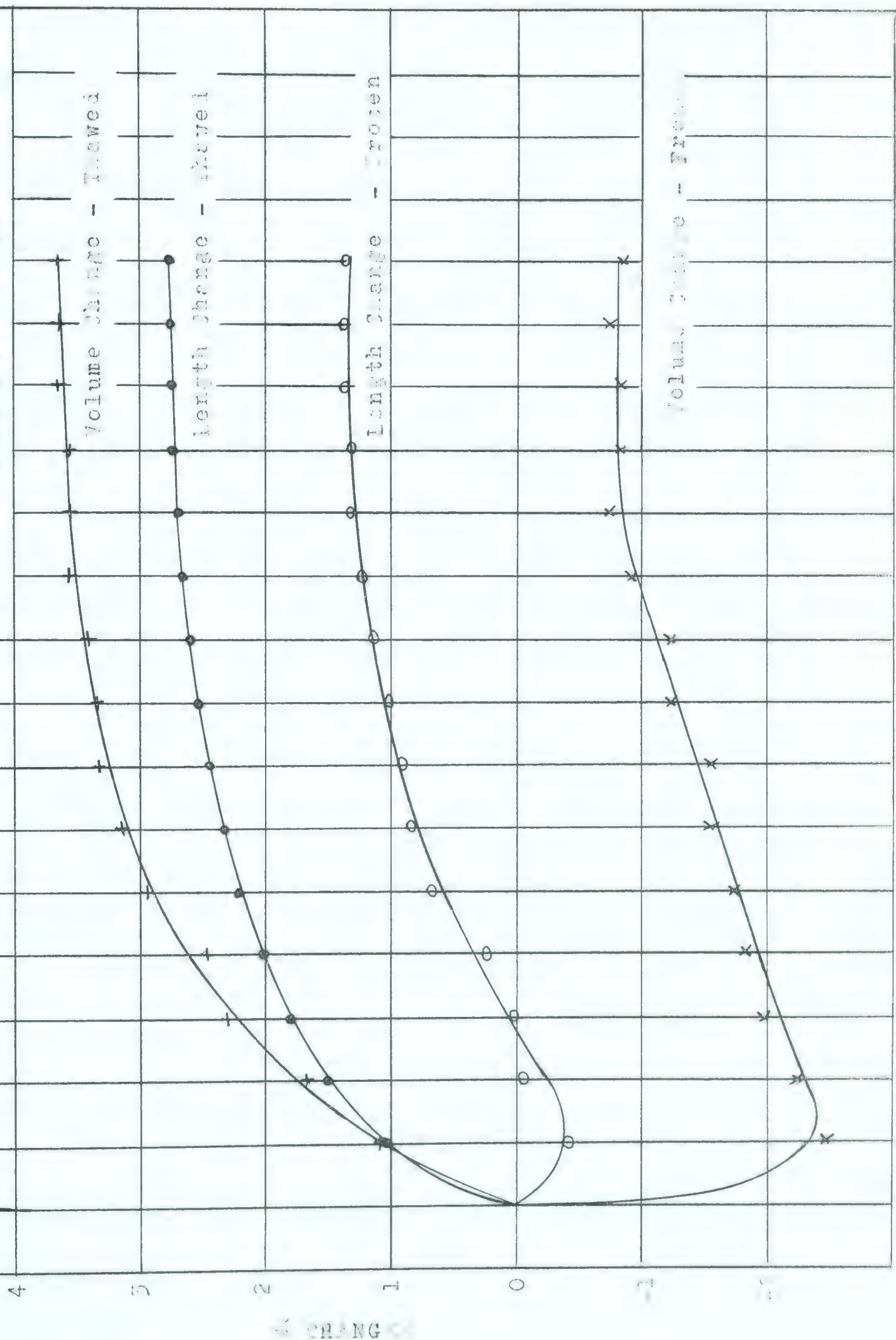
FIGURE 3

GROUP III

LENGTH AND VOLUME CHANGES

70

NUMBER OF JELLS



Considering first Groups I and II, at the same compactive effort, it appears moisture content is a major factor regarding volume change in both the frozen and thawed state. At the lower moisture content, Group I, the thawed volume is greater than the frozen volume, which is in contrast to Group II. Further, both the thawed and frozen volume changes are considerably smaller at the low moisture content.

The effect of increasing the compactive effort (Group III) and decreasing the moisture content has a very marked effect on the frozen volume of this particular soil, causing a reduction in volume, but it produces also a remarkably high thawed volume.

It is interesting to note that the maximum variation between thawed and frozen volume occurs for Group III (i.e. Group III = 4.55%; Group I = 0.8%; Group II = 1.2%).

Length Change

The frozen and thawed length changes parallel each other for all three groups individually, with Group III only showing a shorter frozen length than thawed length. Maximum percent changes are:

	Frozen	Thawed
Group I	+ 2.4%	+ 1.95%
II	+ 3.7%	+ 1.8%
III	+ 1.3%	+ 2.8%

The maximum length increases for Group II occur at about five cycles, after which the lengths gradually decrease. This length decrease was caused by settling and lateral bulging of the specimens during thawing, and due to bearing of the specimens on the small end

demigage points during length measurements, which forced the point into the specimen, giving a shorter reading.

These effects occurred to a noticeable extent only for Group II due to the higher moisture content of the specimens, which resulted in a fairly low strength material.

Although diameter changes were not observed, it would appear that the diameter varies to a lesser degree, percentage wise, than does the length. This can be illustrated by calculating the volume on the basis of no diameter change and using the length changes measured, and comparing this volume to the measured volume. These comparisons show that up to about three cycles the calculated and measured volumes are virtually equal, indicating no diameter change, after which the calculated volume is less than the measured volume, indicating some diameter increase. By assuming the same percentage increase in diameter as in length, the calculated volume exceeds the measured volume in most cases. These are exceptions, especially in Group II where the diameter increases due to bulging which corresponds to a length decrease. In general, there appears to be a greater length change than diameter change, indicating that the direction of the type of compaction used has an influence.

Any changes occurring in the dry density, void ratio and degree of saturation due to freezing and thawing are related directly to volume changes in the specimens. For this reason the factors causing the changes in volume are also the factors causing the resulting changes in density, void ratio and degree of saturation. These are discussed in the following paragraphs.

The pertinent data regarding volume change and water content

are shown in Table III. On the basis of this data, it is evident that the 9% volume increase of water on freezing could account for all the increase in specimen volume for Group I only, and that for Groups I and III some of the expansion of water on freezing occurred into the available void spaces. Group II exhibited a volume increase in excess of that possible on the basis of the 9% increase in the volume of water on freezing alone. Allowing for some added expansion into available pore space it becomes apparent that ice segregation must have occurred to some degree in this group. This was substantiated by observations of specimens used for determining the extent of moisture migration.

The results of the tests conducted employing directional freezing (Appendix B) to determine if moisture migration occurred during freezing, indicated no moisture variation throughout the specimens, regardless of the direction of freezing.

SPECIMEN VOLUME CHANGES DUE TO FREEZE-THAW.

TABLE III.

		Group I	Group II	Group III
Average Volume of Voids Per Specimen at Compaction.	cc.	86	96	87
Average Volume of Water Per Specimen at Compaction.	cc.	75	88	70
Average Available Void Space Per Specimen at Compaction.	cc.	11	8	17
Average Volume Increase of Water on Freezing Per Specimen. (i.e. &9%).	cc.	7	8	6
Average Maximum Volume Increase Per Specimen After Cyclic Freezing	cc.	3	13	Decrease

On the basis of the moisture migration tests on these specimens, which were compacted at the same moisture content as Group II (29.5%), it is likely that ice segregation did not occur to a great extent in Group II specimens. That is, it is likely that no overall moisture migration occurred resulting in a buildup of large ice lenses. However, close visible examination of the frozen specimens, at this moisture content, disclosed small ice lenses, which were probably the result of a local migration of moisture. A combination of the rapid freezing of the specimens, which occurred due to the relatively low temperature of the deep freeze, i.e. 0° F., and the low permeability of the compacted clay probably prevented any excessive moisture migration, but would allow some migration to an ice lense from a limited area and thus the formation of small ice lenses. It should be noted that although all soil water does not freeze at 0° C. and thus a means for moisture migration is available, migration would not occur since there would be no temperature gradient once the specimens were frozen.

The small lenses which occurred were visible mainly in the areas close to the compaction layers, i.e. the planes joining one layer to the layer above it, and were situated in planes at right angles to the specimen length. This would indicate that ice lenses formation is influenced by the direction of compaction, and that lenses begin at irregularities in the compacted soil, i.e. the jointing between two layers. Further, the formation of the lenses in planes at right angles to the length may be the reason why the specimens exhibited a larger percentage length increase than diameter increase during the early freeze-thaw cycles.

The shrinkage of the Group III specimens, and the swelling phenomena exhibited by all the specimens in both the frozen and thawed state could be explained by Winterkorn's theory, which is based on the reduction in volume occurring from water to a high pressure form of ice. In the frozen state the percentage increase in volume for the groups is directly related to the moisture content, with Group II, at the highest moisture content, having the greatest increase in frozen volume and Group III, at the lowest moisture content, showing a decrease in volume when frozen. It is likely that as the moisture content increases there is a corresponding increase in: (a) the amount of free water, i.e. water that is not adsorbed to the clay minerals, or (b) water which is adsorbed with decreased adsorption force. Thus, at the higher moisture content the increased amount of "free" water expands upon freezing into ice as indicated on Figure I. This expansion more than overcomes the shrinkage on freezing of the water which is under high adsorption pressures, resulting in an overall swelling of the specimen. At low moisture contents, i.e. Group III, the majority of the water is under high adsorption pressures and thus the specific volume of the ice formed is less than that of the adsorbed water, resulting in the specimen shrinkage. This theory assumes, of course, that there is a significant difference in particle waterfilms occurring for the changes in moisture content and amounts of compacted soil which exist from group to group.

The above theory would be more applicable to Groups I and III since some ice segregation occurred for Group II. However, ice segregation could occur without invalidating Winterkorn's theory, i.e. both mechanisms may take place simultaneously.

Specimen shrinkage could also be caused in a manner similar to which shrinkage occurs for a soil sample in a shrinkage limit determination. If small ice lenses were formed moisture would be drawn to the lenses from the surrounding soil resulting in a drying of this soil, and a corresponding shrinkage. In specimens at high moisture content (i.e. Group II) the increase in volume due to the formation of the ice lenses would be greater than the shrinkage of the soil resulting in an overall volume increase. For specimens at low moisture content (Group III) the size or number of ice lenses formed would be smaller, the resulting volume increase due to these lenses would be smaller, and an overall volume decrease could occur.

The increase in volume of the specimens in the thawed state over the frozen state for Groups I and III could also be explained by Winterkorn's theory of pressures upon thawing, resulting from the increase in volume from high pressure ice to water.

It is possible that this increase in volume upon thawing may also be related to the air in the voids in a manner somewhat similar to that described by Schmid (9). Initially, the compaction of the specimens may result in the air in the voids being under some pressure. There is air within the loose soil as it is placed in the mold, and this air could become trapped in the specimen as the compactive effort is applied, with further compaction causing the air to become compressed and thus under pressure. This compressed air would be trapped by the low permeability of the compacted specimens, but some air possibly could force its way out of the specimen. This was evident during the period of time immediately after compaction when the specimens were

being coated with latex, as air was being forced out of the specimens and causing bubbles in the latex coating. Upon freezing the combination of the specimens shrinkage and air being released from the moisture upon cooling, could result in an increase in pressure of the air in the voids. Indications that the air in the specimens voids was under a fairly high pressure in the frozen state were given by Group III specimens. During the early freeze-thaw cycles large bulges appeared in the latex coatings of these specimens, and by applying pressure to these bulges with a thumb, it became evident they contained air under pressure. The latex coating became quite hard and non-plastic when frozen, thus allowing pressures to form without rupturing the coating.

It is possible that as the specimen freezes from the outside and shrinks, the majority of the air in the voids becomes trapped by the hard, frozen soil, and if any movement of the air is possible it must be towards the unfrozen centre of the specimen. Thus there could be a build up of air under pressure in the inner portion of the specimen which becomes trapped in the voids by the hard, frozen soil.

When removed from freezing temperatures, the specimen will thaw, with the thawing progressing slowly from the outside towards the centre. It will be subsequently shown that this thawed soil has lost a considerable amount of cohesion due to freezing. Thus the air pressure within the specimen could force this thawed soil outward in all directions from the centre, resulting in an increased volume of the thawed specimens over its frozen volume.

The increased volume of the specimen in the thawed state would mean that more void space would be available, and thus the air pressure

within the specimen could be dissipated into these voids. Upon refreezing, this air would again be trapped within the specimen and pressure built up. A further slight reduction in cohesion upon thawing, would mean a further slight increase in volume upon thawing and thus a progressive increase in thawed volume as cycles of freeze-thaw increases.

It should be noted that this theory is subject to factors which could invalidate it. The most readily apparent is that the air in the voids must follow Boyle's and Charles's Laws. A drop in temperature from 22° centigrade (room temperature) to -18° centigrade (0° F. , which was the temperature of the deep freeze) would reduce the volume of a given amount of air if the pressure was constant by $\frac{40}{273} = 14.7\%$. This reduction in volume would reduce the air pressure in the voids caused by specimen shrinkage.

However, consider a 2% volume decrease for a Group III specimen (Figure X), which must have occurred at the expense of the available void space, since the water and soil grains are virtually incompressible. The available void space in a Group III specimen (Table III) is approximately 17 cc., and 2% of the total volume of the specimen (205 cc.) is approximately 4 cc., which is a $4/17 = 24\%$ decrease in void space. A combination of the 24% decrease in void space and the 15% decrease in the volume of the air in the voids would result in a net 9% decrease in volume of the air in the voids caused by shrinkage pressures, and there would therefore be some increase in pressure in the entrapped air. Further, upon thawing the temperature of this entrapped air will rise and this will cause a tendency towards an increase in volume of the air, which will result in a gain in air pressure. Thus Charles's Law does

not necessarily invalidate this theory.

Boyle's Law need not be considered since pressures resulting are a result of volume changes in the air and not a cause of volume changes.

It is the opinion of the author that specimen volume changes occurring due to freezing and thawing are a result of a combination of factors rather than any single one. Winterkorn's theories of shrinkage upon freezing and expansion upon thawing have not been repudiated by any authority to this writer's knowledge, and appear to be valid.

However, regarding specimen shrinkage, ice lensing must result in the drying of a portion of the specimen soil. The reduction in volume of a soil upon drying is evidenced by shrinkage limit tests, indicating some specimen shrinkage could occur by this method.

Similarly, the air pressure theory cannot be completely ignored since the occurrence of the air bubbles on the specimens in the frozen state indicate some air pressure occurred. Since these air bubbles did not appear in the thawed state it is assumed that the air pressure was dissipated upon thawing by expansion of the specimen.

CHAPTER V.

DISCUSSION OF RESULTS OF STRENGTH VARIATION.

The variations of compressive strength of the compacted specimens with cycles of freeze-thaw and of the "stand-by" specimens are shown on Figures XI, XII and XIII for Groups I, II, and III, respectively. The curves below the zero line indicate the percent loss in compressive strength for varying lateral pressures as cycles increase, and the curves above the zero line indicate the percent gain, or tendency for strength gain as time increases (i.e. corresponding to number of cycles).

Due to the erratic variation of some results the curves are "best-fit" curves, the placing of which may warrant criticism. In some instances a point which varies considerably from the general trend of other points has been ignored, especially in the curves for the stand-by specimens. For Group III the curves showing strength gain have not been plotted since the results scattered so widely that no reasonable curves could be drawn. However, the scatter of the points about the zero line are indicative that no strength increase with time took place for these specimens.

It should also be noted that the percentage compressive strength gain or loss was calculated on the basis of the results of one series of tests of the specimens after compaction, which corresponds to the "zero" cycle. These specimens also exhibited some erratic variation in results from that which normally would be expected. Since these results

FIGURE II
PERCENT CHANGE OF VIBRATION PERIOD
WITH CYCLES OF VIBRATION-THAM
AT VARIOUS INTERNAL PRESSURES
GROUP I

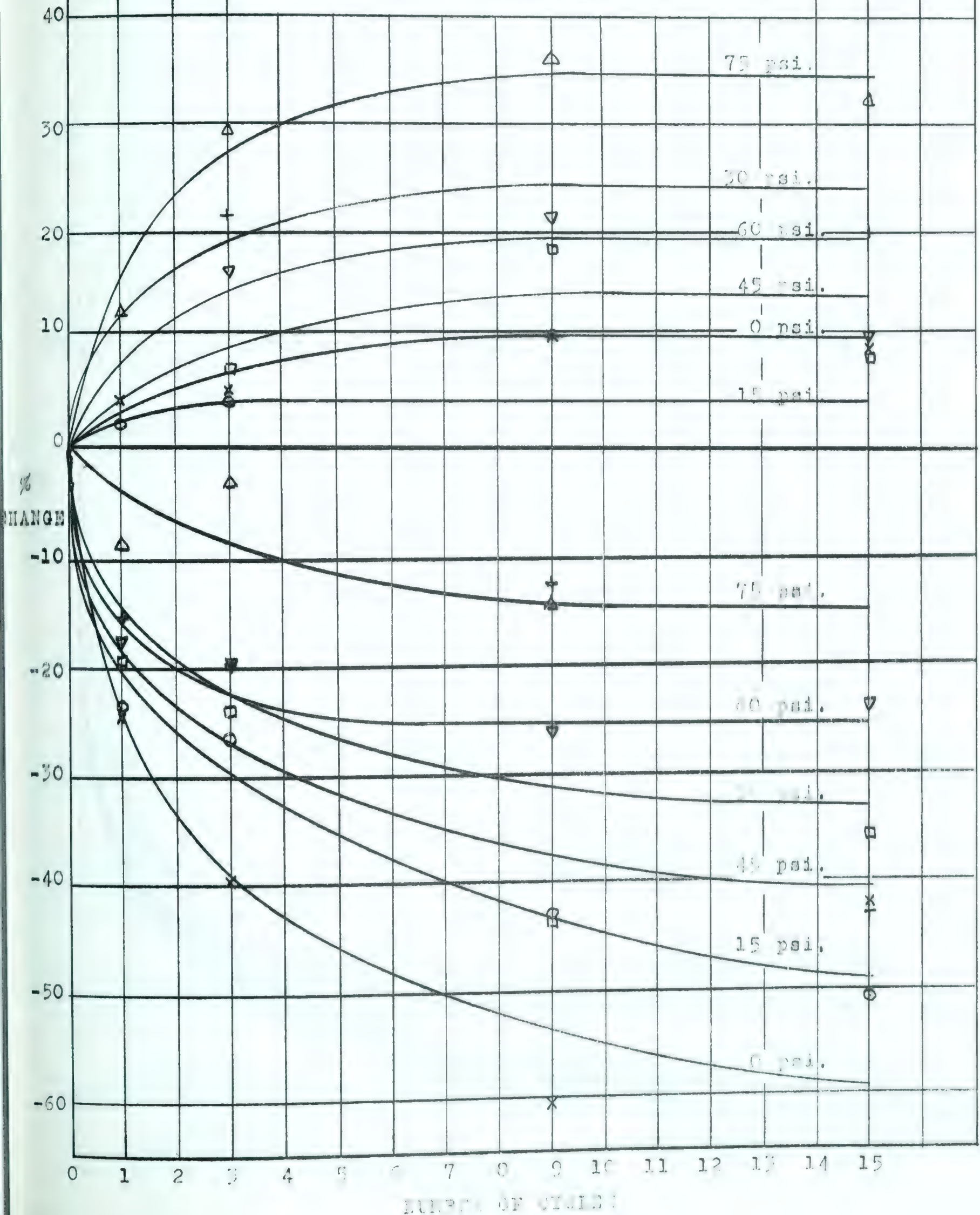


FIGURE XII
 PERCENT CHANGE OF EVIATOR STRAIN
 WITH CYCLES TO FAILURE-TWAN
 AT VARIOUS LATERAL PRESSURES
 GROUP II

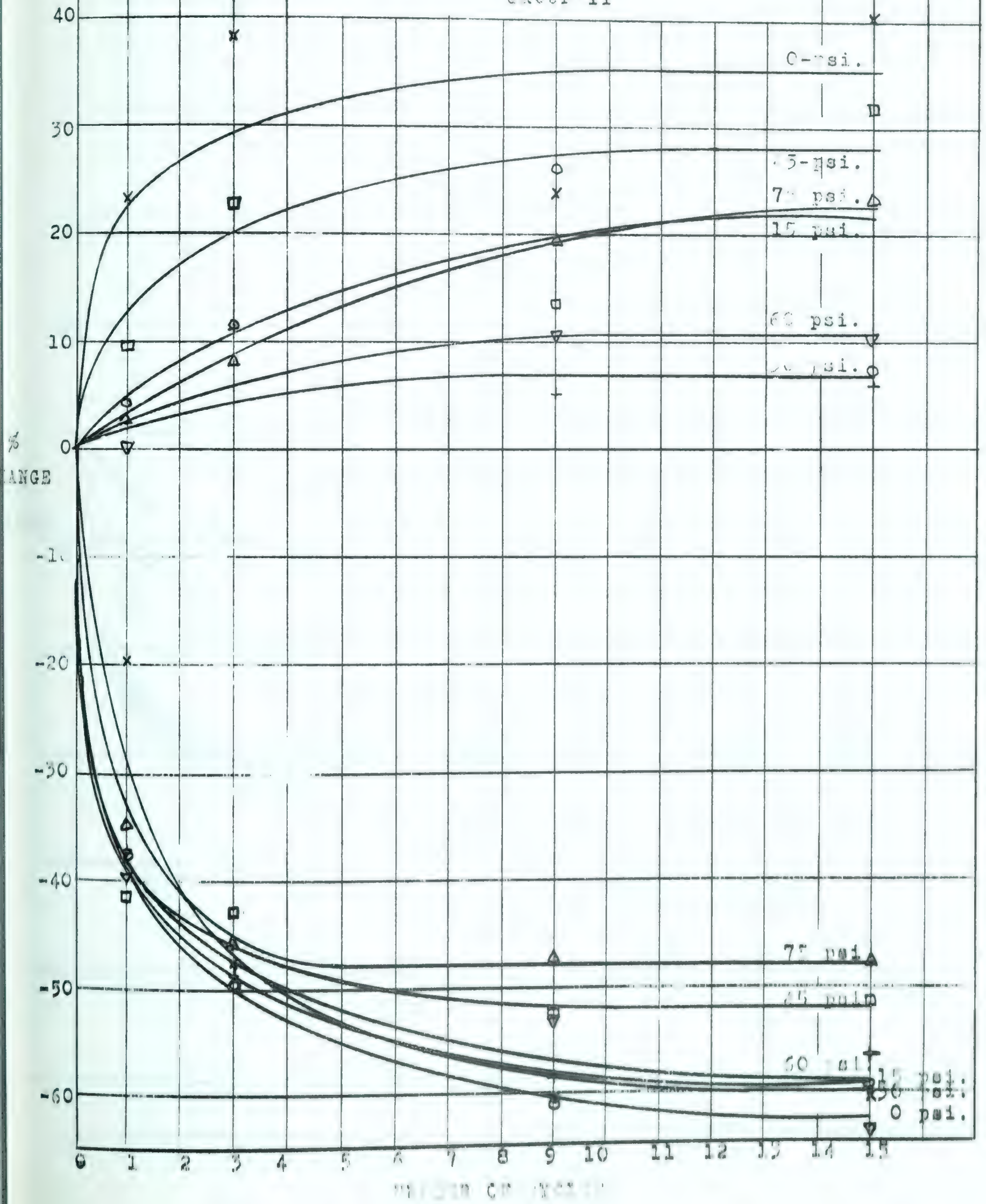
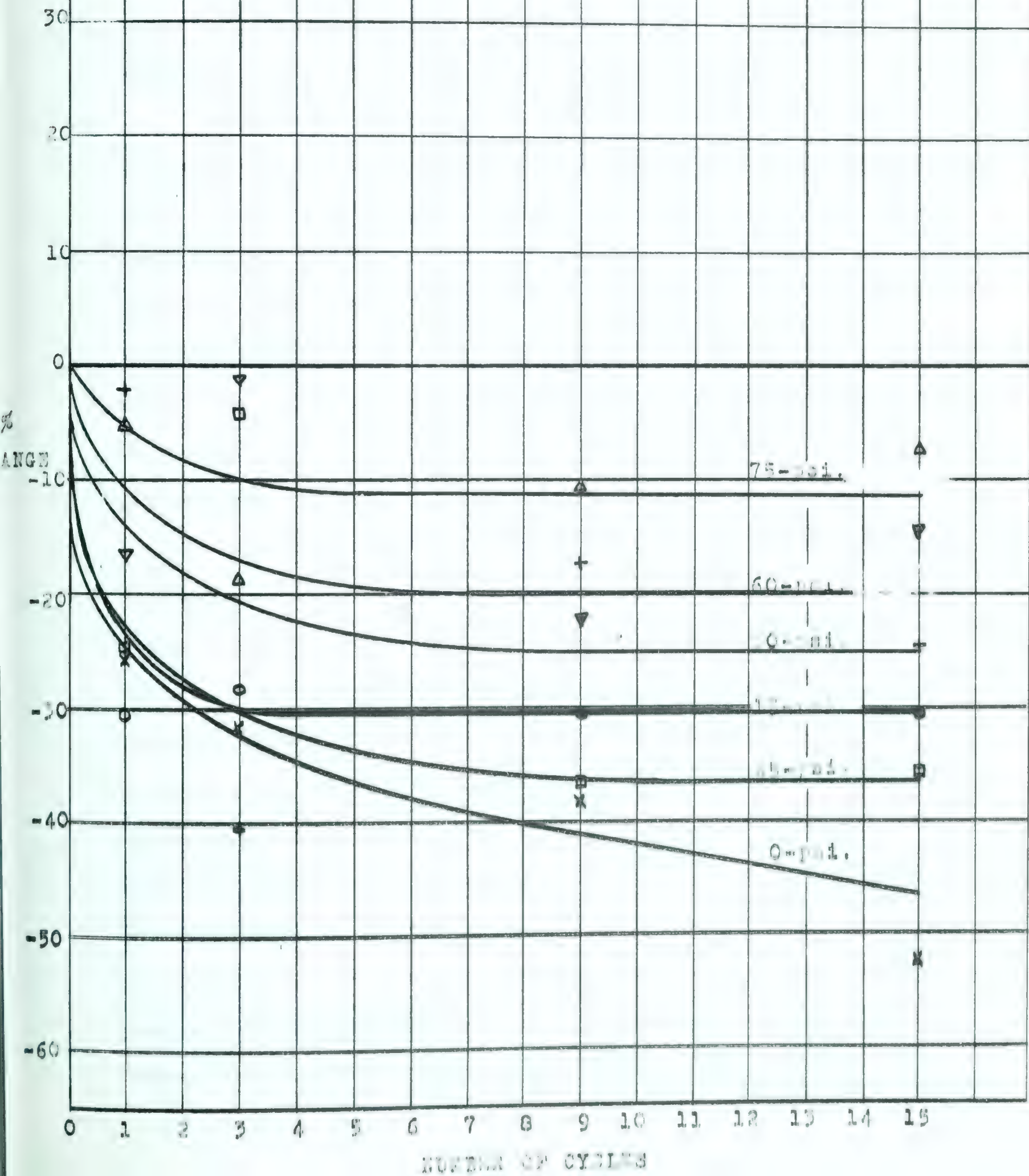


FIGURE III
 PERCENT CHANGE OF TENSILE STRESS
 WITH YEARS OF SERVICE
 AT VARIOUS LAYERS OF WALLS
 GROUP III



were assumed to be correct, the percent strength change of some subsequent specimens consequently appear to be erratic, although the test value may not be. However, the strength loss due to freezing is, in most cases, large enough that this erratic variation of the zero-cycle specimens does not affect the percent change too greatly.

The majority of detrimental effects on strength of compacted clay specimens appears to occur within the first three cycles of freeze-thaw. This is most pronounced for Group II but is generally true for the other groups as well. The high moisture content group (Group II) shows the highest percent strength loss, reaching as high as 60%. The lowest strength loss is exhibited by Group III (maximum of approximately 40% in unconfined state) indicates density and the corresponding decreased moisture content results in better resistance to loss of strength from frost action.

All groups show a reduction in percent strength loss as the confining test pressure increases, with this being especially evident for Groups I and III. For example, at 9 cycles, Group III for the unconfined tests shows a percent strength loss of 40%, whereas at a confining pressure of 75 psi., the strength loss is only approximately 10%. This would indicate that the unconfined state is the "worst" condition that exists, and that compacted soils under actual field conditions with some confinement could be expected to have strengths higher than unconfined strengths.

It is also of interest that at high confining pressures the curves of percent strength loss level off at relatively few cycles, whereas the unconfined curves level off after 12 or 15 cycles. This

would indicate that specimens tested at higher confining pressures will not show any strength loss after a limited number of cycles of freeze-thaw. Thus if compressive strength loss due to closed system freeze-thaw were used as a soil test it would not require more than three or four cycles if tested at high confining pressures (i.e. 50 psi. or more).

The curves for the soil tested indicate that 5 cycles of freeze-thaw in a closed system would give a good indication of the maximum amount of strength loss which would occur, regardless of the number of cycles of freeze-thaw, and independent of confining test pressure. However at low confining test pressures (0 to 30 psi.) this would be an indication only, and more accurate results would require 10 or 15 cycles of freeze-thaw. Thus if some correlation between the strength loss at 1 or 2 cycles and the strength loss at an unlimited number of cycles could be established by a large number of tests; or if a relation between the strength loss at a confining pressure of, say, 75 psi. and any other confining pressure could be established, the time and work required for a cyclic freeze-thaw test as a feasible subgrade design test could be reduced.

The noticeable strength increase of the "stand-by" specimens with moisture content remaining constant may be attributed to thixotropic effect. Although the position of these curves may be criticized, the general trend does indicate a strength gain which would average, on the basis of all specimens, between 10% and 20%. The curves for Group III have not been plotted since the points scattered so widely about the zero percent line that it was impossible to draw any curves through them. However, the scatter of the results for these specimens indicate that

for Group III there is very little, if any, increase in strength with time.

The results of some phases of this work can be compared to the results of work done by Ross (23). Ross tested four clay subgrade soils varying in plasticity from low to high, compacted to standard and modified Proctor densities and then subjected to a freeze-thaw and capillary saturation cycles. In each case the samples were frozen and thawed in a system in which no external water was available. Between thawing and freezing the samples were permitted to become saturated by capillarity.

Ross found that all samples decreased in strength, the greatest loss occurring during the first two cycles. He also found that the soils compacted to the higher density maintained a greater strength than those compacted to a lower density, and that all ones tested showed a decrease in density with cycles of freeze-thaw. Thus, the results of these portions of Ross's work are virtually analagous to the results of similar phases of this investigation, although the test procedures are different.

The major difference in testing procedures was the availability of water to the specimens between thawing and freezing in Ross's work, as compared to the closed system in this investigation. Since the results are similar it would appear that the availability of water at this stage only, does not produce any startling results, but a variation in degree of change (density, strength) only. Since differnt soils were used in this work and in Ross's work, comparison of actual values would be meaningless.

Cohesion and Angle of Internal Friction.

Figures XIV, XV, and XVI represent the Mohr plots for the majority of the specimens tested in each group. The plots for the "stand-by" specimens are missing since they would contribute little of significance.

The envelopes for each Group were plotted on the same figures for comparison purposes. They can best be deciphered by considering the upper, or 0 cycles envelope first. The zero point for this series of Mohr circles is the uppermost zero on the scale, with each successive lower zero corresponding to the next successive lower envelope.

Again, the positioning of the envelopes or curves possibly warrants criticism. The erratic results at higher pressures are quite evident on these plots and the general inconsistency of results are also evident. In each case, the Mohr envelope was drawn by placing a line which was a "best-fit" curve for the portions of the circles drawn. The points at higher pressures were partially ignored in that the straight portion of the envelopes were drawn by placing a line which was a "best-fit" straight line for the first 3 or 4 circles, and then flattening the curves so that it included these erratic points somewhat. In the majority of cases the points at lower lateral pressures did not line up too well and for this reason the placing of the straight portion is subject to question. An analytic method for plotting the envelopes was not used because, although the results at higher confining pressures are consistently erratic, they are not erratic to the same degree and thus could result in misleading results.

For a partial defence of the method of drawing these envelopes,

STRESSING STRESS - PSI.

GROUP I

0 CYCLES

1 CYCLE

3 CYCLES

6 CYCLES

12 CYCLES

TOTAL STRESS - PSI

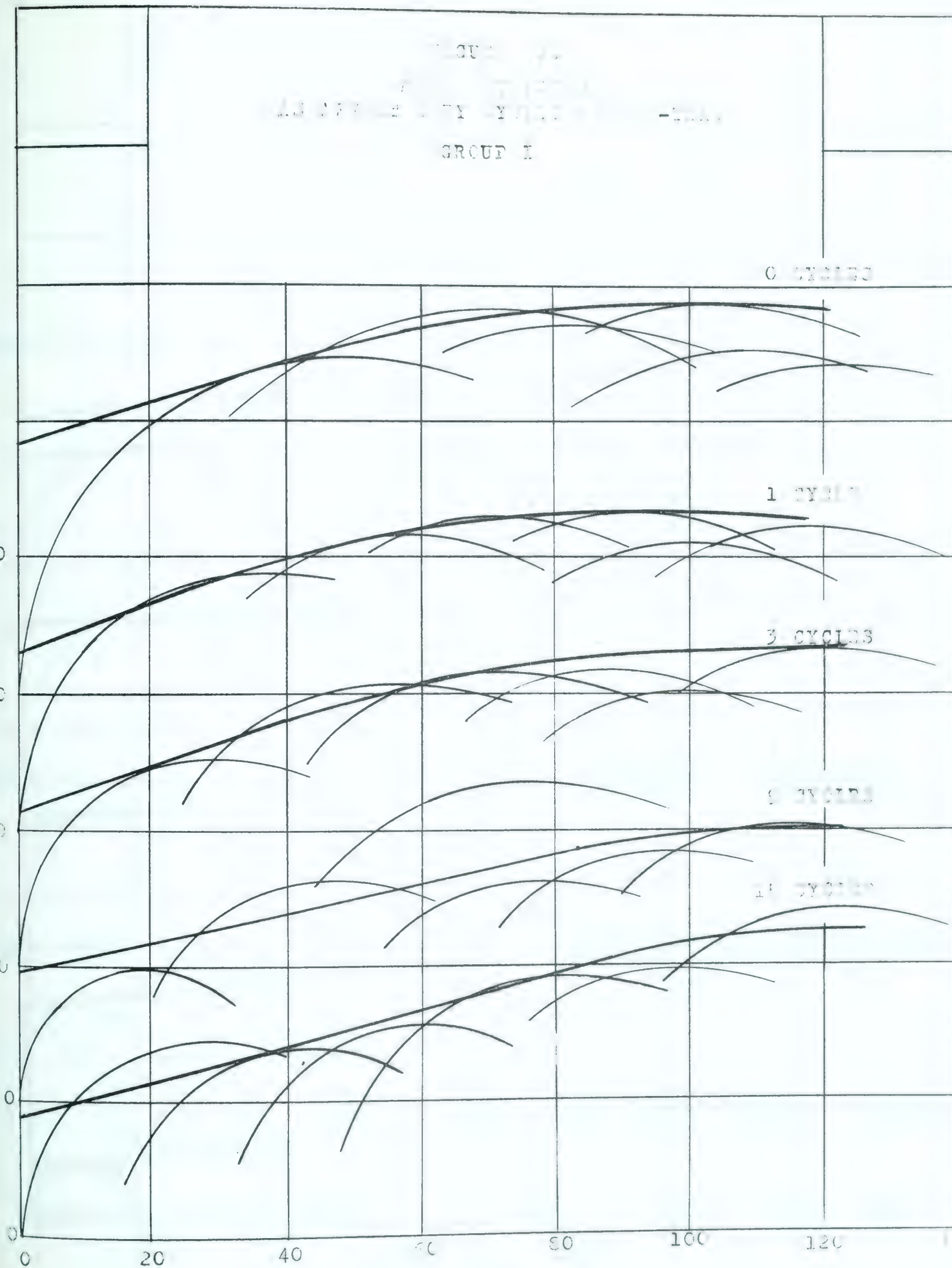


FIGURE IV
MOHR ENVELOPES
AS AFFECTED BY CYCLIC FREEZE-THAW
GROUP II

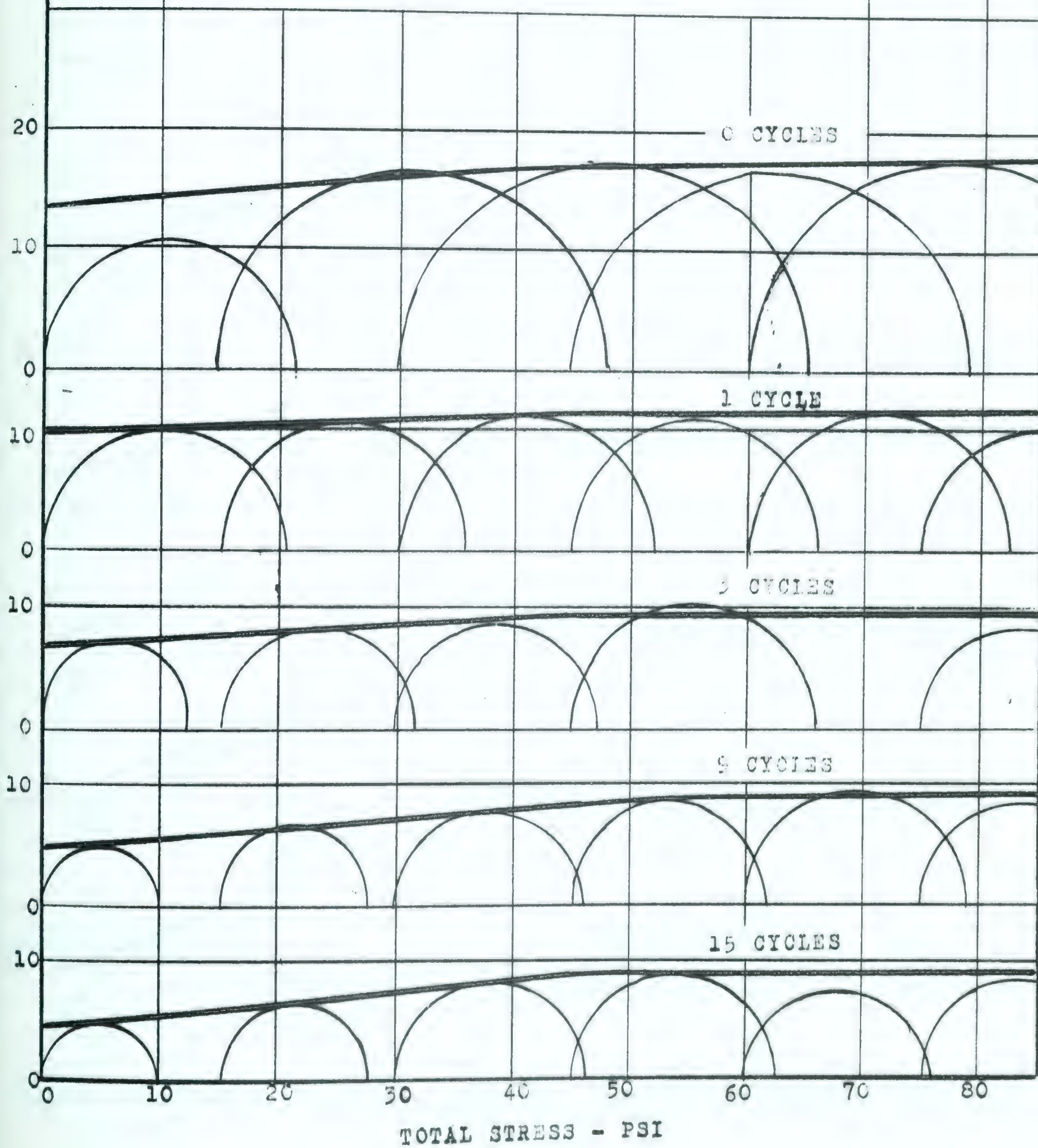
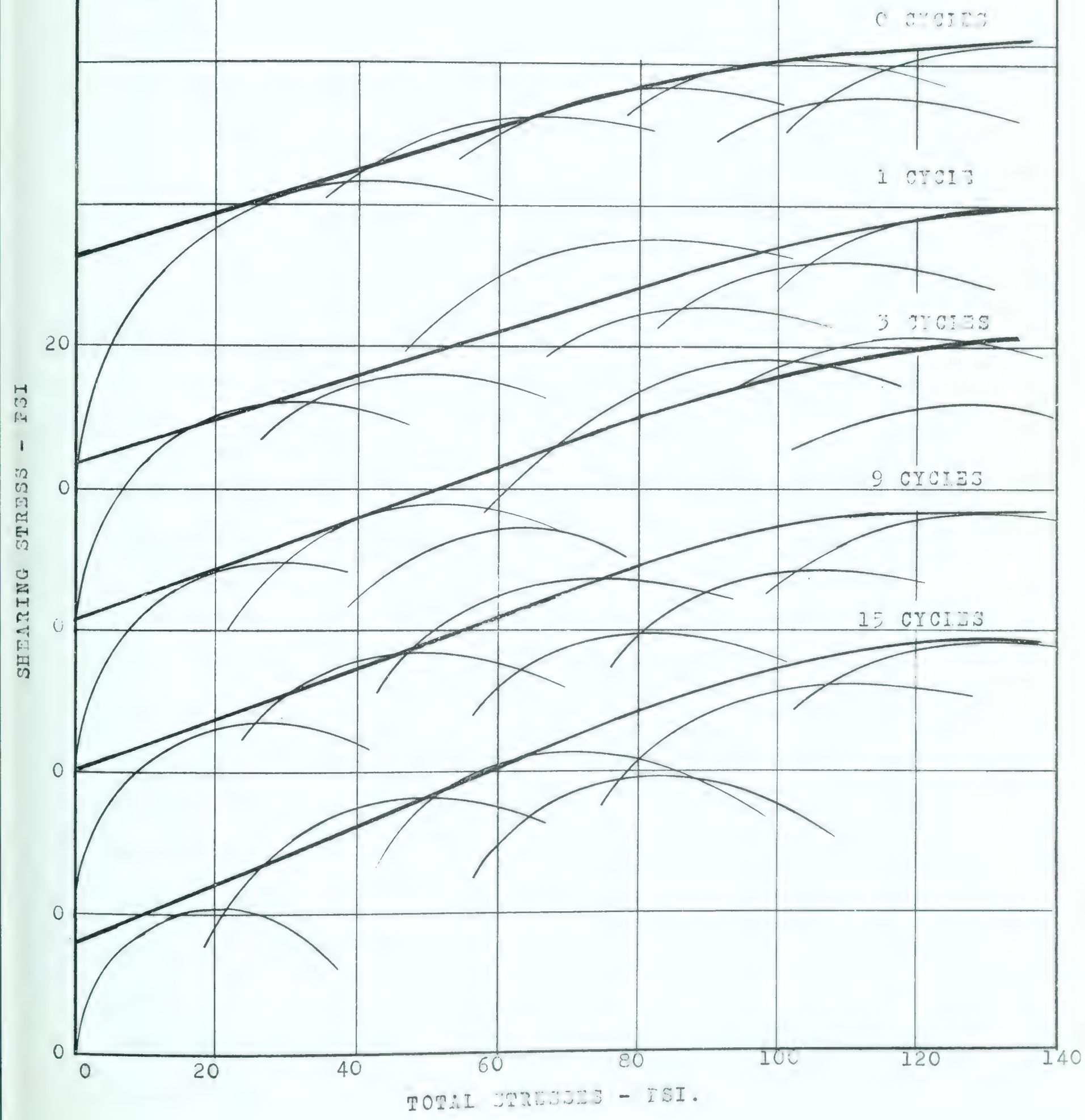


FIGURE XVI
AS AFFECTED BY THE NUMBER OF CYCLES
GROUP III



a brief study of the test results, Appendix A, is required. The stand-by specimens tested at 15 cycles will be studied first. Due to an oversight during testing, 5 specimens of this series were tested in an unconfined test. Below are the deviator stress readings and the specimen moisture contents for these specimens.

Deviator Stress (psi.)	Moisture Content (%).
83.6	20.8
108.2	20.6
103.7	20.8
92.1	22.1
93.3	21.6
Average - 96.2	

Variation from smallest to largest - 24.6

Largest % variation from average - +13.1 %
-12.5%

These results show the large variation of specimen strength which occurred for the specimens tested in the same manner and, for the first three specimens above, at virtually the exact same moisture content. If this series of specimens can be considered as good indication of the variation occurring for all specimens tested, and it probably can, except that the degree of variation may change from group to group, then this specimen variation could account for the erratic test results. Consider that if each stress circle were within $\pm 10\%$ error, then a straight line could be drawn tangent to all the circles by moving the circle within its $\pm 10\%$ error radius until it became tangent.

Further, a study of the majority of the results shows that the specimens, in a series of six tested, which have a relatively low strength, usually have a higher moisture content than the other specimens in the series. This variation in moisture content may be as high as 1.5% from the average.

It is possible that a combination of the above two factors could cause the erratic results, even those at the higher lateral pressures. Since at higher lateral pressures the specimens are becoming more saturated, the Mohr envelopes should curve and tend to level off. In this range the average specimen strength variation from, say, a lateral test pressure of 45 psi. to a test pressure of 60 psi. would be less than the average specimen strength variation from test pressures of 0 to 15 psi. Thus it is possible that the within specimen variation is evident in the higher lateral pressures only, because of the smaller average specimen strength variation between successive increments of lateral pressure. In this way the low strength results at confining test pressures of 45 psi, and 60 psi. could be explained by strength variation within the specimens; or by a slightly lower average moisture content of the specimens tested at confining pressures of 45 psi. and 60 psi. and thus a resulting lower strength; or by a combination of all three of the above.

However, although it is possible the discrepancies at these high confining pressures could be explained by natural within specimen variation the consistency of the lower strengths at high confining pressures perhaps indicate some structural change is occurring. This line of reasoning is possibly borne out by the results of a consolid-

ation test run on a compacted specimen, Appendix C. The results of this test showed the swelling pressure of the compacted soil was approximately 45 psi., which corresponds to the confining pressures at which the majority of the lower strengths were first observed in each series.

Although the exact significance of this data is not known, it could be possible that in some way, when the confining pressure equals the swelling pressure of the compacted specimen, some structural change occurs, the effect of which is to lower the strength of the specimen. This, however, is merely conjecture and it would be necessary to run a considerable number of consolidation tests in accordance with triaxial compression tests with pore pressure measurements to determine if there is any relation between swelling pressure and structural change of compacted clays.

Regardless of the exact positioning of the envelopes it appears that cyclic freeze-thaw considerably reduces the cohesion of compacted, highly plastic clay, but has a lesser effect on the angle of internal friction. The cohesion and angle of internal friction values for the envelopes drawn on Figures XIV, XV, and XVI, are shown in the following table.

TABLE IV.

Cohesion and Angle of Internal Friction As Affected By Cycles of
Freeze-Thaw.

No. of Cycles	0	1	3	9	15
<u>Group I</u>					
Cohesion (psi.)	37	26	22	19	17
% loss in cohesion	-	29.9	40.6	48.7	54.0
Angle of Internal Friction (degrees)	18 ⁰	19 ⁰	18.5 ⁰	13 ⁰	15 ⁰
<u>Group II</u>					
Cohesion (psi.)	13.5	9.5	7	5	4.5
% loss in cohesion	-	29.6	48.2	63.0	70.4
Angle of Internal Friction (degrees)	5 ⁰	3 ⁰	4 ⁰	5 ⁰	6 ⁰
<u>Group III</u>					
Cohesion (psi.)	33	24	22	21	17
% loss in cohesion	-	27.3	33.3	36.3	48.5
Angle of Internal Friction (degrees)	18 ⁰	18 ⁰	13.5 ⁰	19 ⁰	21 ⁰

The plots and Table IV show the largest percentage loss of cohesion occurs within one cycle of freeze-thaw, with additional losses as cycles increase. The largest angle of friction occurred for the modified Proctor compaction at modified optimum moisture content, Group III. Group II, compacted at a moisture content above standard optimum exhibits a very small angle of friction, and the envelopes level off at a confining pressure of about 30 psi., indicating the specimens have become practically saturated at this pressure.

It should be emphasized that the significance of these results is not the values of the cohesion and angle of internal friction which were obtained, since they are subject to question, but it is the trends indicated and the overall effects of freeze-thaw on the compacted clay which are of significance.

The test results, Figures XI, XII, and XIII, show conclusively that there is a definite loss in strength due to freezing and thawing which need not be accompanied by a corresponding total increase in moisture content. This strength loss occurred at all confining pressures, but was most pronounced for the unconfined tests. The greatest percent loss in strength occurred in the group of specimens at the highest moisture content. (Group II).

The exact cause of strength loss due to freezing and thawing at constant moisture content is not readily apparent. Plots of dry density, void ratio, and degree of saturation versus compressive strength were attempted, but no definite trends or relationships could be established. These plots were hampered by the availability of only one result at each confining pressure for each testing cycle. Regardless of this it became

apparent that neither the density, void ratio nor degree of saturation are the factors governing the strength loss. That is, although the density is decreased, for example, by cyclic freeze-thaw, and there is an accompanying loss in strength, the density decrease is not the sole factor governing the strength loss, but rather a lesser contributing factor. Of these three factors mentioned above, the decrease in density due to the freezing and thawing is most likely to have the greatest effect on strength. Since the degree of saturation was decreased by the freeze-thaw cycling, it should not contribute to a strength loss, and the increase in void ratio which occurred is virtually similar to the decrease in dry density and so this factor can be ignored.

Motl (6) attributed strength loss on freezing of clays to a change in structure in the soil. Variations in structure of frozen clays have been reported (7) but the manner with which these changes in structure affect the strength are not known.

A close study of the frozen, compacted specimens, which were used for moisture migration tests, showed the compacted soil divided by small white frost lines into small lumps or nuggets of compacted soil. These small nuggets did not appear to be affected by the freezing, in that no visible frost lines or crystals appeared in them to the naked eye. Upon thawing, the soil mass appeared as a cluster of these small lumps with small cracks appearing between the lumps.

Although no overall moisture migration occurred, as indicated by directional freezing tests, Appendix B, it is suggested that migration occurred on a local scale, i.e. possibly from within the small lumps or nuggets to the frost lines dividing these nuggets. It is further

suggested that the moisture in the specimen froze in the same manner at each cycle of freezing, and in relatively the same place.

This would be possible if the moisture which migrated from within each nugget during the freezing cycle returned to relatively the same position inside the nugget during the thawing period. Since the rapid freezing allowed very little time for migration, water could not migrate far, and therefore, would not have far to return to its former position by whatever forces would act upon it. But, since movement to the nuggets during thawing probably proceeds at a slower rate than does moisture migration away from the nuggets during freezing, the nugget structure becomes more developed as cycles proceed.

Thus, it is possible that for each cycle of freeze-thaw, the soil mass is broken into the same small nuggets each time, until these nuggets become separate, individual masses of soil. These nuggets are separated by cracks, and the structure of the specimen may be compared with that of a sample of gravel in which each small stone in the gravel represents a small soil nugget in the soil specimen. Unlike gravel, however, the nuggets, in addition to having a very small frictional resistance at points of contact, would also have some cohesion or adhesion at these points.

The test results have indicated that while freezing causes a marked decrease in the cohesion value of the specimen strength, there was very little variation in the value of the angle of internal friction. Further, Table IV shows that the angle of internal friction varies with the moisture content, i.e. the lower the moisture content, the higher the angle of internal friction. The second factor could be explained

by consideration of the adsorbed water films on the soil particles. At the higher moisture contents, the adsorbed water films are larger, the moisture is on the average, under less adsorption forces and thus there is a greater lubrication between particles and a resultant lower angle of friction.

The effect of freezing and thawing on the strength loss characteristics of the compacted clay soil could possibly be explained in the following manner. When a load is applied to a specimen which has been frozen and thawed, and which exhibits nugget structure, these nuggets will be forced together. Since the moisture content of each nugget is essentially the same throughout the specimen, the adsorbed water films of the soil particles of each nugget will be the same. The angle of internal friction of soil sample is determined by the friction between the individual soil particles, and therefore, there should be little variation in the angle of internal friction whether the soil is in the form of individual particles, or in the form of nuggets made up of individual particles. In this way it would be possible to explain why the angle of internal friction of a soil which has been frozen and thawed, and has formed nugget structure, would not vary greatly from the angle of internal friction for the same soil at the same moisture content^{which} has not been frozen.

Prior to loading a specimen, the cohesion or adhesion between nuggets would be very small and would occur only at contact points. Upon loading, further cohesion would develop between surfaces at right angles to the direction of loading. When the specimen is loaded to failure and the specimen fails by shearing it follows that the shear

plane would pass between soil nuggets with cohesion varying from a small to a relatively large amount. This would occur since the shear plane would occur at an angle of roughly $45^{\circ} + \phi/2$, and therefore would pass between nuggets which could have developed a large amount of cohesion on their horizontal faces, a small amount of cohesion on their vertical faces, and an intermediate amount on their diagonal faces.

The reduced loss in strength, and therefore, cohesion, of the specimens subjected to cyclic freeze-thaw, as confining pressure increased, could be explained by the nugget structure. As the confining pressure increases the cohesion or adhesion on the vertical or diagonal faces of the nuggets would be increased, and thus the resistance to shear between nuggets would be increased, and the specimen strength increased.

Also, the additional loss in strength as cycles increase could be explained by the further reduction in cohesion between nuggets which occurs as the nuggets become more and more separated as cycles increase.

CHAPTER VI.

CONCLUSIONS AND RECOMMENDATIONS.

The results of this investigation have indicated the following conclusions and recommendations for future research. Conclusions drawn are specifically applicable to the partially saturated, highly plastic clay used in this project.

Conclusions.

1. There is a definite loss in the compressive strength of the soil tested when subjected to cyclic freezing and thawing at constant moisture content. These strength losses appear to be due to a structural change in the clay caused by the cyclic freeze-thaw, resulting in a large reduction in cohesion of the soil, and a relatively minor change in angle of internal friction.
2. The volume change and length change characteristics of a partially saturated, compacted, highly plastic clay in a closed system appear to be influenced primarily by the original moisture content of the soil, and to a lesser degree by the degree of compaction.
3. Cyclic freezing and thawing of a compacted clay specimen produces a thawed volume which is in excess of the original compacted volume, and may produce a frozen volume either smaller or larger than the original compacted volume. These changes in thawed volume produce
 - 1). Decreases in the dry density.
 - 2). Decreases in the degree of saturation.

3). Increases in the void ratio.

These resulting changes in dry density, degree of saturation and void ratio which occur are not related directly to, and are not the major cause of the corresponding loss in compressive strength which occurs.

4. Successive cycles of freeze-thaw will not produce extensive moisture migration within a compacted clay specimen in a closed system, when rapid freezing is employed.

5. Ice lensing can occur under the conditions imposed in the tests, but only on a very small scale, the extent of which is determined by the moisture content of the soil.

6. A partially saturated compacted highly plastic clay will gain strength if left undisturbed at constant moisture content.

7. Compacted clay specimens which have been subjected to cyclic freeze-thaw exhibit the greatest percent strength loss when tested in an unconfined test

8. Increased compaction and a corresponding reduction in moisture content appears to reduce the effects of cyclic freeze-thaw on clay but does not eliminate them.

Recommendations.

Further investigations should be carried out on the effect of freeze-thaw on the strength of compacted clay soils. If tests are conducted for the purpose of determining only the extent of the strength loss caused by freeze-thaw cycling, then unconfined tests should be used. If, however, tests are conducted for the purpose of determining the cause of any strength decrease, then it is imperative that tests be conducted in a triaxial cell and pore air and pore water pressure measurements be made, to determine effective stresses.

The consolidation test conducted in this report indicate that there is possibly some relation between the swelling pressure of a compacted clay specimen and the strength characteristics. It is suggested that consolidation tests be run on compacted specimens in addition to triaxial tests with pore pressure measurements, to determine if any relationship does exist.

It is thought by the author that a very small change in moisture content (1 to 2%) of a compacted clay can produce a substantial change in the compressive strength of the specimen. Studies could be made regarding this point. The major difficulty would be in obtaining an equal distribution of moisture throughout the soil sample during mixing. It is recommended that a method of mixing the moist soil other than hand mixing be used. The method of adding moisture using a spray system as developed by the Research Council of Alberta is recommended for moistening the soil.

Further investigations could be made in an attempt to determine what is the exact cause for an increase in volume of a thawed

specimen over both its frozen volume and original volume. The exact nature of these proposed tests is not known but possibly some relationship between moisture content or degree of compaction and the amount of swelling or thawing would be established.

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APPENDIX A

SUMMARY OF THE TEST DATA.

SUMMARY OF RESULTS--GROUP I

SPECIMEN NUMBER	MOISTURE CONTENT %	HEIGHT (in.)	DRY WT. (gms.)	VOLUME (c.c.)	(lb./ft ³)	VOLUME OF VOIDS(c.c.)	VOID RATIO	S (%)	(psi.)	(psi.)
					I CYCLE					
2	23.4	3.987	317.8	206.7	95.9	92.1	.804	80.8	0	75.5
12	23.4	3.987	316.7	207.1	95.6	92.7	.810	80.0	15	86.3
20	23.6	3.987	319.9	206.6	96.4	91.2	.790	83.0	30	91.5
30	23.3	3.987	317.4	206.5	95.9	92.0	.803	80.3	45	92.2
38	24.3	3.987	319.5	206.1	96.8	90.8	.786	86.0	60	82.4
48	23.3	3.987	317.4	206.8	95.7	93.0	.806	80.0	75	87.7
					3 CYCLES					
4	23.8	3.987	317.1	208.3	95.2	93.8	.819	80.4	0	60.2
14	23.8	3.987	317.1	207.5	95.5	93.1	.814	81.0	15	83.2
22	23.7	3.987	319.3	209.8	95.4	94.6	.821	80.0	30	86.8
32	23.7	3.987	317.4	209.7	94.6	95.2	.831	79.0	45	86.7
40	24.7	3.987	318.1	207.6	95.8	92.7	.807	85.0	60	80.2
50	23.7	3.987	316.3	206.8	95.5	92.6	.810	81.1	75	92.8
					9 CYCLES					
6	24.4	3.987	318.0	212.1	93.7	97.2	.839	80.0	0	58.2
16	24.0	3.987	318.5	211.9	93.9	96.9	.842	79.1	15	64.5
24	23.4	3.987	318.7	207.7	96.0	92.6	.803	80.5	30	94.5
34	25.0	3.987	318.9	212.1	93.8	96.9	.840	82.4	45	64.2
42	24.7	3.987	318.8	210.9	94.5	96.0	.836	82.1	60	73.8
52	24.0	3.987	318.3	206.5	96.3	91.3	.789	83.7	75	82.2
					15 CYCLES					
26	23.7	3.987	319.0	206.9	96.0	92.1	.801	82.0	0	57.9
44	25.1	3.987	318.2	206.2	96.5	91.3	.795	87.5	15	55.6
18	24.4	3.987	317.2	208.8	94.9	94.3	.823	82.1	30	62.0
54	24.3	3.987	316.9	206.3	95.9	92.0	.805	83.7	45	79.1
8	26.5	3.987	317.2	210.4	94.2	95.9	.836	87.6	60	77.5
36	24.2	3.987	319.2	211.4	94.4	96.4	.838	80.3	75	97.9

SPECIMEN NUMBER	MOISTURE CONTENT %	HEIGHT (in.)	DRT WT. (gms.)	VOLUME (c.c.)	(lb./ft. ³)	VOLUME OF VOIDS(c.c.)	VOID RATIO	S (%)	(psi.)	(psi.)
AS COMPACTED										
1	23.3	4.030	317.7	205.0	96.5	90.4	.789	82.3	0	99.6
10	23.6	4.030	317.3	205.0	96.4	90.5	.797	86.3	15	113.1
19	23.6	4.030	317.0	205.0	96.4	90.6	.792	86.0	30	107.8
28	22.8	4.030	318.6	205.0	96.8	90.0	.783	86.9	45	114.0
37	23.4	4.030	318.8	205.0	96.0	89.9	.781	86.5	60	100.0
46	23.5	4.030	317.8	205.0	96.5	90.3	.787	86.0	75	95.7
STAND-BY TO 1 CYCLE										
3	23.2	4.030	318.3	205.0	96.8	90.1	.785	85.4	0	104.2
11	22.6	4.030	319.4	205.0	97.0	89.7	.778	83.8	15	115.5
21	22.4	4.030	317.7	205.0	96.5	90.4	.789	82.0	30	121.7
29	24.1	4.030	319.4	205.0	97.0	89.7	.778	89.5	45	119.3
39	24.0	4.030	318.8	205.0	96.9	89.9	.781	88.6	60	101.6
47	22.4	4.030	318.6	205.0	96.8	90.0	.783	82.8	75	107.9
STAND-BY TO 3 CYCLES										
5	22.4	4.030	316.3	205.0	96.1	90.8	.795	81.3	0	104.7
13	23.2	4.030	317.6	205.0	96.1	90.8	.795	85.0	15	117.9
23	22.5	4.030	318.7	205.0	96.9	90.0	.783	83.1	30	130.8
31	22.2	4.030	318.0	205.0	96.6	90.2	.786	81.6	45	123.7
41	22.9	4.030	318.1	205.0	96.7	90.2	.786	84.0	60	116.0
49	23.8	4.030	317.8	205.0	96.5	90.3	.787	87.2	75	123.7
STAND-BY TO 9 CYCLES										
51	23.1	4.030	321.1	205.0	97.5	89.1	.770	86.9	0	110.0
43	24.4	4.030	317.9	205.0	96.5	90.3	.787	89.4	15	91.9
33	24.0	4.030	318.0	205.0	96.5	90.3	.787	88.0	30	106.6
25	22.6	4.030	317.3	205.0	96.4	90.5	.791	82.5	45	135.6
15	23.4	4.030	317.2	205.0	96.4	90.5	.791	85.6	60	121.6
7	22.7	4.030	317.2	205.0	96.4	90.5	.791	82.9	75	130.5
STAND-BY TO 15 CYCLES										
27	24.1	4.030	317.7	205.0	96.5	90.4	.789	88.4	0	108.8
35	23.7	4.030	319.6	205.0	97.1	89.6	.777	87.9	15	106.6
9	22.8	4.030	319.8	205.0	97.3	89.6	.777	87.3	30	130.0
53	22.0	4.030	321.6	205.0	97.8	89.0	.760	83.8	45	123.3
17	24.2	4.030	318.6	205.0	96.9	90.0	.783	89.4	60	110.0
45	23.5	4.030	317.7	205.0	96.5	90.4	.789	86.0	75	127.0

SUMMARY OF VOLUME AND LENGTH CHANGES - GROUP I

SPECIMEN NUMBER	ORIG. LENGTH (in.)	FINAL LENGTH (in.)	ORIG. VOL. (meas.) (c.c.)	FINAL VOL. (meas.) (c.c.)	INCREASE (c.c.)	ORIG. VOL. (calc.) (c.c.)	FINAL VOL. (meas.) (c.c.)	FINAL VOL. (calc. from length) (c.c.)
I CYCLE								
2	3.987	4.023	207.9	209.6	1.7	205.0	206.7	206.7
12	3.987	4.029	208.5	210.6	2.1	205.0	207.1	207.1
20	3.987	4.025	210.6	212.2	1.6	205.0	206.6	206.8
30	3.987	4.023	209.1	210.6	1.5	205.0	206.5	206.8
38	3.987	4.025	211.0	212.1	1.1	205.0	206.1	206.8
48	3.987	4.036	210.1	211.9	1.8	205.0	206.8	207.2
3 CYCLES								
4	3.987	4.056	208.2	211.4	3.2	205.0	208.2	208.2
14	3.987	4.042	209.4	211.9	2.6	205.0	207.5	207.8
22	3.987	4.055	209.8	214.6	4.8	205.0	209.8	208.2
32	3.987	4.054	208.4	213.1	4.7	205.0	209.7	208.2
40	3.987	4.037	210.9	212.5	2.6	205.0	207.6	207.9
50	3.987	4.038	210.2	212.0	1.8	205.0	206.8	207.4
9 CYCLES								
6	3.987	4.100	209.5	216.6	7.1	205.0	212.1	210.6
16	3.987	4.084	209.7	216.6	6.9	205.0	211.9	210.0
24	3.987	4.049	209.9	212.6	2.7	205.0	207.7	208.2
34	3.987	4.077	210.8	217.9	7.1	205.0	212.1	209.5
42	3.987	4.077	211.0	216.9	5.9	205.0	210.9	209.5
52	3.987	4.045	211.0	212.5	1.5	205.0	206.5	207.9
15 CYCLES								
26	3.987	4.045	209.1	211.0	1.9	205.0	206.9	207.9
44	3.987	4.045	211.1	212.3	1.2	205.0	206.2	207.9
18	3.987	4.065	210.2	214.0	3.8	205.0	208.8	208.9
54	3.987	4.049	208.6	209.9	1.3	205.0	206.3	208.1
8	3.987	4.074	210.7	216.1	5.4	205.0	210.1	209.0
36	3.987	4.073	210.4	216.7	6.4	205.0	211.4	209.4

SUMMARY OF RESULTS--GROUP II										
SPECIMEN NUMBER	MOISTURE CONTENT %	HEIGHT (ins.)	DRY WT. (gms.)	VOLUME			VOID RATIO	S (%)	(psi.)	(psi.)
				(c.c.)	(lb./ft. ³)	VOIDS(c.c.)				
AS COMPACTED										
21	29.5	4.065	308.6	207.9	92.8	96.5	.866	93.5	0	23.7
1	28.8	4.044	310.0	208.0	93.1	96.1	.859	92.3	15	32.4
11	28.7	4.036	314.3	207.7	94.6	94.2	.839	89.4	30	35.7
51	27.8	4.037	305.5	207.7	90.4	99.3	.914	91.6	45	35.0
31	28.8	4.044	309.6	208.0	92.9	96.3	.863	92.2	60	36.1
41	LEAK									
STAND-BY TO 1 CYCLE										
3	28.7	4.043	310.3	207.9	93.3	95.9	.855	92.4	0	29.2
13	28.8	4.050	308.0	208.3	92.4	97.0	.871	91.3	15	33.5
23	28.7	4.046	309.1	208.0	92.8	97.5	.874	90.5	30	34.7
33	27.8	4.030	313.0	207.3	94.3	94.2	.834	92.0	45	38.0
43	28.3	4.043	309.5	208.0	92.9	96.4	.864	90.4	60	33.2
53	28.4	4.051	308.3	208.3	92.4	97.1	.873	89.9	75	33.0
STAND-BY TO 3 CYCLES										
5	28.7	4.050	309.1	208.3	92.6	96.8	.868	91.2	0	33.0
15	28.7	4.050	309.1	208.3	93.0	96.2	.861	90.1	15	36.1
25	28.1	4.030	310.8	207.2	93.7	95.1	.849	91.5	30	38.7
35	28.0	4.038	311.2	207.5	93.6	95.3	.848	91.0	45	42.6
45	28.8	4.037	308.6	207.5	93.9	96.1	.863	91.9	60	37.2
55	29.3	4.045	307.9	208.0	92.3	97.0	.874	92.6	75	34.7
STAND-BY TO 9 CYCLES										
7	29.4	4.041	305.8	207.9	91.9	97.7	.885	93.0	0	29.4
17	28.1	4.039	308.8	207.7	93.9	96.3	.864	90.3	15	40.7
27	28.7	4.044	308.4	207.7	92.5	97.0	.868	91.9	30	36.6
37	28.7	4.036	309.3	207.5	93.1	95.9	.859	92.6	45	39.3
47	28.8	4.048	306.4	208.3	91.9	97.7	.884	90.4	60	37.0
57	28.8	4.035	307.0	207.5	92.4	96.7	.874	91.5	75	38.4
STAND-BY TO 15 CYCLES										
9	28.6	4.055	308.3	208.4	93.4	97.2	.874	91.0	0	33.5
19	29.2	4.031	306.3	207.2	92.4	96.6	.874	93.0	15	34.8
29	28.8	4.042	307.8	207.9	92.2	97.1	.877	91.1	30	36.9
39	28.0	4.025	310.6	207.1	93.6	95.1	.850	91.5	45	45.7
49	30.3	4.055	302.6	208.4	90.7	99.2	.906	92.7	60	36.7
59	28.6	4.050	306.5	208.3	91.9	97.6	.883	90.0	75	39.6

SUMMARY OF RESULTS--GROUP II

SPECIMEN NUMBER	MOISTURE CONTENT %	HEIGHT (in.)	DRY WT. (gms.)	VOLUME (c.c.)	(lb./ft. ³)	VOLUME OF VOIDS(c.c.)	VOID RATIO	S (%)	(psi.)	(psi.)
I CYCLE										
2	29.3	4.044	307.1	209.7	91.4	98.8	.891	90.7	0	19.1
12	28.9	4.042	309.5	210.0	91.9	98.2	.880	90.5	15	20.2
22	29.0	4.037	308.9	210.4	91.5	98.8	.885	90.1	30	22.6
32	29.2	4.039	308.5	210.3	91.5	98.8	.886	90.9	45	20.9
42	29.8	4.044	306.6	210.5	90.8	99.7	.901	91.0	60	22.8
52	29.6	4.042	306.6	210.6	90.8	99.8	.901	90.6	75	20.9
3 CYCLES										
4	29.1	4.044	306.1	214.2	89.2	103.6	.937	85.5	0	12.5
14	29.4	4.026	304.4	214.4	88.5	104.4	.950	85.4	15	16.35
24	29.3	4.040	306.3	216.2	88.4	105.5	.954	84.8	30	16.75
34	29.0	4.034	309.0	215.4	89.4	103.8	.930	85.8	45	20.8
44	LEAK									
54	30.2	4.048	303.2	208.1	90.7	108.7	.993	83.6	75	17.55
9 CYCLES										
6	29.0	4.039	306.1	219.2	89.7	108.6	.984	82.0	0	9.42
16	29.0	4.044	308.6	214.7	90.2	102.2	.919	87.8	15	12.7
26	28.7	4.033	308.8	217.2	88.6	105.2	.946	83.9	30	15.7
36	29.3	4.042	307.5	220.1	89.8	109.1	.984	82.6	45	16.85
46	29.3	4.050	306.2	215.3	88.8	104.6	.950	85.0	60	18.25
56	29.4	4.047	307.3	218.3	87.6	107.4	.970	84.1	75	16.85
15 CYCLES										
8	28.8	4.030	308.5	214.4	89.7	103.1	.927	86.2	0	9.42
18	29.0	4.033	308.0	219.0	87.5	107.9	.970	82.5	15	13.05
28	29.0	4.036	310.4	219.1	88.5	107.0	.955	84.1	30	16.3
38	29.3	4.031	308.4	218.5	87.5	107.5	.969	83.2	45	17.4
48	29.9	4.039	304.6	211.8	89.8	101.8	.925	89.6	60	14.7
58	29.6	4.038	306.1	218.6	87.4	108.0	.927	84.0	75	16.7

SUMMARY OF VOLUME AND LENGTH CHANGES - GROUP II

SPECIMEN NUMBER	ORIG. LENGTH (in.)	FINAL LENGTH (in.)	ORIG. VOL. (meas.) (c.c.)	FINAL VOL. (meas.) (c.c.)	INCREASE (c.c.)	ORIG. VOL. (calc.) (c.c.)	FINAL VOL. (meas.) (c.c.)	FINAL VOL. (calc. from length) (c.c.)
I CYCLE								
2	4.044	4.079	216.2	217.9	1.7	208.0	209.7	209.7
12	4.042	4.094	216.7	218.8	2.1	207.0	210.0	210.3
22	4.037	4.094	215.0	217.9	2.9	207.5	210.4	210.3
32	4.039	4.037	216.5	219.1	2.6	207.6	210.2	210.1
42	4.042	4.094	216.7	219.3	2.6	207.9	210.5	210.3
52	4.044	4.090	217.1	219.7	2.6	208.0	210.6	210.2
3 CYCLES								
4	4.044	4.107	214.8	221.0	6.2	208.0	214.2	211.0
14	4.026	4.096	215.2	222.8	7.6	206.8	214.4	210.4
24	4.040	4.143	215.5	224.2	8.7	207.5	216.2	212.3
34	4.034	4.127	216.0	224.2	8.2	207.2	215.2	212.3
44	4.040	4.119	216.9	225.2	8.3	207.5	215.8	211.8
54	4.048	4.054	217.0	217.0	0	208.1	208.1	208.2
9 CYCLES								
6	4.039	4.115	215.5	227.1	11.6	207.6	219.2	211.4
16	4.039	4.076	215.4	221.1	5.7	208.0	213.7	209.5
26	4.033	4.120	217.6	227.6	10.0	207.2	217.2	211.9
36	4.042	4.139	215.7	227.5	12.2	207.9	220.1	212.7
46	4.050	4.038	216.3	223.5	7.2	208.1	215.3	210.2
56	4.047	4.098	215.9	226.2	10.3	208.0	218.3	210.7
15 CYCLES								
8	4.030	4.064	216.3	223.7	7.4	207.0	214.4	209.0
18	4.033	4.113	215.7	227.4	11.8	207.2	219.0	211.2
28	4.036	4.107	215.6	227.4	11.8	207.3	219.1	211.0
38	4.031	4.113	215.5	226.9	11.4	207.1	218.5	211.2
48	4.039	4.027	216.6	220.8	4.2	207.6	211.8	206.9
58	4.038	4.078	216.2	227.3	11.1	207.5	218.6	209.6

SUMMARY OF RESULTS--GROUP III

SPECIMEN NUMBER	MOISTURE CONTENT %	HEIGHT (in.)	DRY WT. (gms.)	VOLUME (c.c.)	(lb./ft ³)	VOLUME OF VOIDS(c.c.)	VOID RATIO	S (%)	(psi.)	(psi.)
1 CYCLE										
2	22.8	3.992	325.3	207.5	97.9	90.1	.768	81.9	0	65.2
10	21.1	3.998	320.6	207.8	96.4	92.0	.794	73.5	15	73.7
18	20.8	3.991	326.8	207.6	98.2	89.5	.758	75.8	30	110.7
26	22.2	3.987	327.0	207.9	98.3	89.7	.758	80.8	45	91.4
34	22.1	3.980	327.2	206.9	98.6	88.7	.750	81.0	60	103.7
42	21.7	3.996	329.3	207.2	99.3	88.3	.743	80.5	75	120.0
3 CYCLES										
4	22.4	3.982	326.7	208.3	97.9	90.3	.776	80.5	0	59.7
36	22.1	3.993	324.8	209.6	96.9	92.3	.768	77.3	15	75.9
28	23.5	3.990	326.0	209.0	97.4	91.3	.776	83.2	30	67.3
12	21.1	3.996	325.1	210.1	96.6	92.8	.791	76.0	45	116.5
20	21.3	3.993	328.4	210.0	97.6	91.6	.771	76.0	60	122.5
44	22.0	4.000	325.4	211.0	96.3	93.6	.796	76.6	75	102.8
9 CYCLES										
6	21.4	3.997	325.7	212.9	95.5	95.4	.811	72.8	0	54.2
14	20.8	3.990	323.6	212.1	95.2	95.2	.815	70.7	15	73.3
22	21.3	3.984	326.3	211.3	96.5	93.4	.792	74.6	30	93.2
30	22.7	3.985	321.7	211.7	95.0	95.5	.831	76.7	45	76.8
38	22.1	3.987	326.0	211.4	96.3	93.7	.796	77.1	60	96.3
46	21.7	3.991	329.0	212.8	96.5	94.0	.793	76.1	75	112.7
15 CYCLES										
8	21.6	3.983	326.1	213.8	95.5	95.9	.813	73.5	0	41.7
16	20.6	3.993	325.0	213.2	95.3	95.9	.816	69.8	15	73.3
24	21.6	3.986	327.6	212.6	96.1	94.4	.797	75.0	30	85.3
32	22.4	3.995	327.0	212.6	96.1	94.4	.812	76.4	45	78.0
40	22.0	3.990	327.0	213.3	95.8	95.3	.806	75.6	60	106.3
48	21.4	3.992	327.7	214.3	95.4	96.0	.811	73.1	75	117.4

SUMMARY OF RESULTS--GROUP III

SPECIMEN NUMBER	MOISTURE CONTENT %	HEIGHT (in.)	DRY WT. (gms.)	VOLUME (c.c.)	(lb./ft. ³)	VOLUME OF VOIDS(c.c.)	VOID RATIO	S (%)	(psi.)	(psi.)
AS COMPACTED										
1	22.4	3.990	331.9	205.5	100.9	85.7	.715	86.5	0	87.6
9	20.6	3.988	326.8	205.5	99.5	87.5	.742	76.8	15	105.9
17	20.7	3.987	326.9	205.5	99.5	87.4	.740	77.5	30	112.8
25	21.2	3.990	326.9	205.5	99.5	87.4	.740	79.5	45	121.4
33	22.2	3.990	327.3	205.5	99.6	87.3	.738	83.4	60	111.9
41	21.5	3.997	329.0	205.9	100.0	87.0	.733	81.5	75	126.4
STAND-BY TO 3 CYCLES										
3	22.2	3.990	326.2	205.5	99.3	87.7	.745	82.8	0	85.8
11	20.4	3.985	330.4	204.7	100.8	85.3	.715	78.9	15	100.2
27	23.1	3.980	326.6	205.0	100.0	86.5	.732	87.1	30	91.6
19	20.4	3.986	330.1	204.7	100.6	85.6	.719	78.4	45	131.5
35	21.4	3.986	329.8	204.7	100.5	85.8	.722	82.6	60	112.5
43	21.0	3.997	331.6	205.8	100.6	86.1	.720	81.0	75	134.3
STAND-BY TO 9 CYCLES										
5	22.0	3.981	323.2	204.5	98.8	87.7	.751	81.1	0	86.2
13	20.9	3.990	324.7	205.5	98.9	88.1	.750	75.9	15	101.6
21	21.1	3.990	327.9	205.5	99.1	87.2	.736	79.2	30	120.5
29	22.9	3.987	322.7	205.5	98.2	88.8	.738	83.1	45	95.0
37	21.9	3.984	327.6	204.7	99.9	86.6	.733	82.8	60	124.6
45	21.7	3.995	327.2	205.7	99.4	87.7	.743	81.0	75	135.9
STAND-BY TO 15 CYCLES										
7	20.8	3.986	322.2	204.7	98.5	88.3	.758	76.0	0	83.6
15	20.6	3.984	327.1	204.7	99.8	86.7	.735	77.5	0	108.2
23	20.8	3.982	325.6	204.6	99.6	87.1	.741	77.5	0	103.7
31	22.1	3.982	325.6	205.6	99.0	87.5	.745	82.1	0	92.1
39	21.6	3.986	329.1	204.7	100.2	85.8	.722	82.9	0	93.3
47	21.0	3.992	328.0	205.5	99.8	87.1	.736	78.9	30	123.5

SUMMARY OF VOLUME AND LENGTH CHANGES - GROUP III

SPECIMEN NUMBER	ORIG. LENGTH (in.)	FINAL LENGTH (in.)	ORIG. VOL. (meas.) (c.c.)	FINAL VOL. (meas.) (c.c.)	INCREASE (c.c.)	ORIG. VOL. (calc.) (c.c.)	FINAL VOL. (meas.) (c.c.)	FINAL VOL. (calc. from length) (c.c.)
I CYCLE								
2	3.992	4.040	212.3	214.7	2.4	205.1	207.5	207.7
10	3.998	4.042	213.1	215.5	2.4	205.4	207.8	207.9
18	3.998	4.034	213.1	215.9	2.6	205.0	207.6	207.3
26	3.987	4.040	213.1	216.1	3.0	204.9	207.9	207.7
34	3.980	4.019	212.4	214.7	2.3	204.6	206.9	206.5
42	3.996	4.044	212.5	215.4	2.9	205.3	207.2	208.0
3 CYCLES								
4	3.982	4.052	212.6	216.2	3.5	204.7	208.3	208.3
36	3.993	4.068	212.5	217.0	4.5	205.1	209.6	209.2
28	3.990	4.063	212.8	218.0	5.2	204.9	210.1	208.9
12	3.990	4.062	212.8	218.0	5.2	204.9	210.1	208.9
20	3.993	4.070	213.4	218.3	4.9	205.1	210.0	209.2
44	4.000	4.060	212.8	218.0	5.2	205.6	211.0	208.7
9 CYCLES								
6	3.997	4.107	215.1	220.5	7.4	205.5	212.9	211.3
14	3.990	4.095	212.9	220.0	7.1	205.0	212.1	210.5
22	3.984	4.088	212.6	219.1	6.5	204.8	211.3	210.2
30	3.985	4.089	212.6	219.4	6.8	204.8	211.6	210.2
38	3.987	4.091	213.0	219.5	6.5	204.9	211.4	210.3
46	3.991	4.103	212.4	220.2	7.8	205.0	212.8	211.2
15 CYCLES								
8	3.983	4.108	212.6	221.5	8.9	204.7	213.8	211.3
16	3.993	4.112	213.0	221.1	8.1	205.1	213.2	211.4
24	3.986	4.103	212.7	220.4	7.7	204.9	212.6	211.6
32	3.995	4.110	212.8	220.0	7.2	205.4	212.6	211.3
40	3.990	4.112	212.8	221.0	8.2	205.1	213.3	211.4
48	3.992	4.117	212.8	221.9	9.1	205.3	214.3	211.7

APPENDIX B

ADDITIONAL FINDINGS OF THE

FIGURE XVII

SEGMENTS SELECTED FOR MOISTURE CONTENT
DETERMINATIONS OF SPECIMENS SUBJECTED TO
DIRECTIONAL FREEZING

1
2
3
4
5
6
7
8

SPECIMEN FROZEN
FROM UPPER END

3
5
6
7
8
4

SPECIMEN SUBJECTED
TO ALL-ROUND FREEZING

SUMMARY OF MOISTURE CONTENTS OF SPECIMEN SECTIONS

FOR DIRECTIONAL FREEZING TESTS

END FREEZING

SPECIMEN SECTION	NUMBER OF CYCLES						
	0	1	2	3	5	7	9
1	29.5	29.2	29.5	29.7	28.2	29.9	29.7
2	29.8	29.4	29.7	29.5	29.0	29.8	29.5
3	29.6	29.6	29.4	29.4	28.6	28.6	29.0
4	29.9	29.6	29.4	29.3	28.5	29.0	28.7
5	29.8	29.7	29.3	29.2	28.3	28.8	28.6
6	29.7	29.8	29.6	29.4	28.4	28.6	29.1
7	29.8	29.7	29.5	29.2	28.4	29.6	29.2
8	29.6	29.8	29.8	29.6	28.7	28.9	28.6

ALL-ROUND FREEZING

SPECIMEN SECTION	NUMBER OF CYCLES						
	0	1	2	3	5	7	9
1	29.5	29.6	29.8	29.9	29.4	28.7	29.3
2	29.4	29.7	29.8	29.6	29.5	29.9	29.2
3	29.5	29.6	29.3	29.0	28.8	28.6	28.9
4	29.8	29.8	29.4	30.0	29.3	29.5	29.2
5	29.7	29.6	29.2	29.2	28.4	28.7	28.8
6	29.9	29.6	29.2	29.0	28.7	29.1	29.3
7	29.7	29.4	29.4	29.5	29.2	29.4	29.1
8	29.6	29.7	29.5	29.3	29.3	29.5	28.9

NOTE --- All Moisture Contents in Percent.

APPENDIX C
CONSOLIDATION
TEST

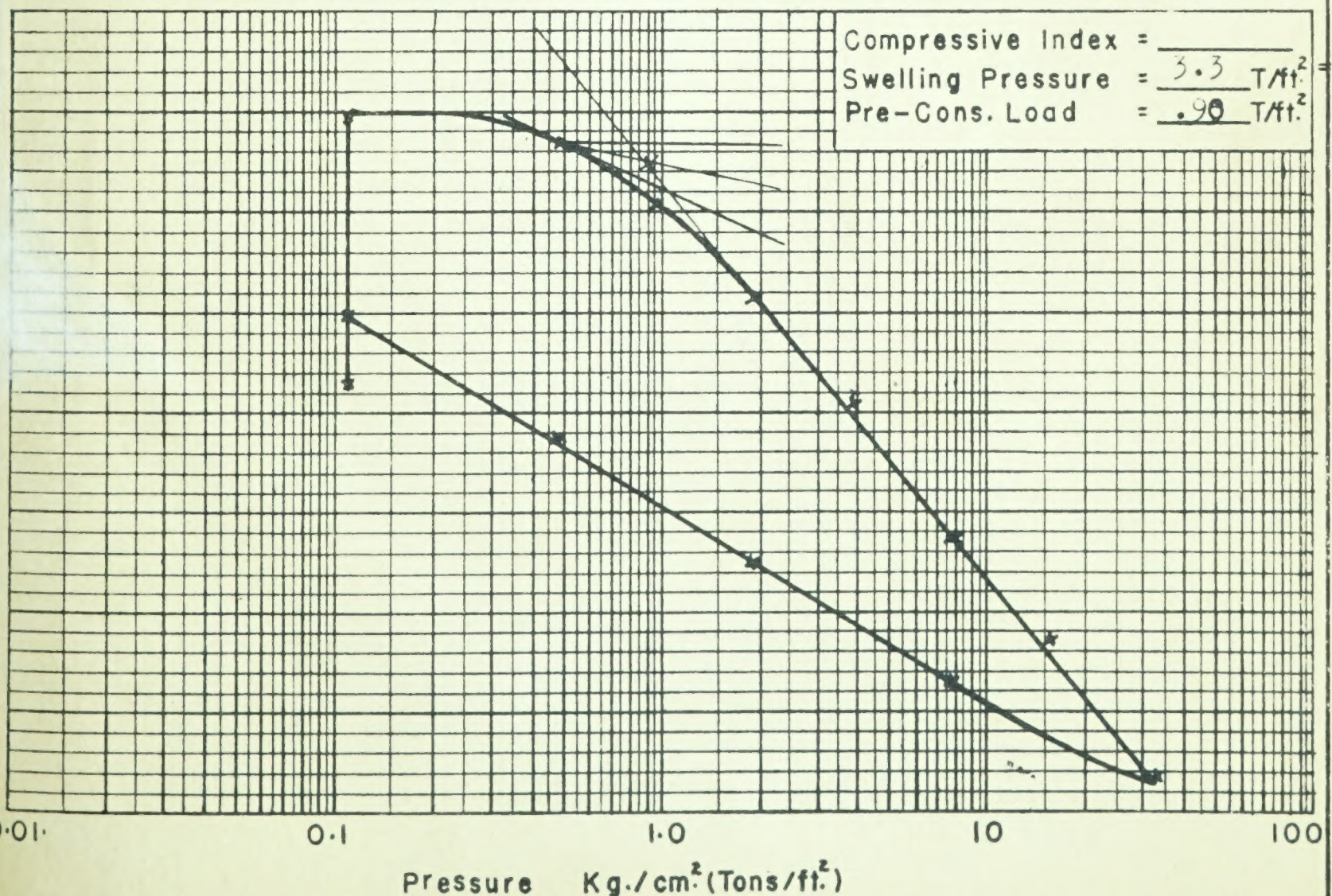
UNIVERSITY of ALBERTA
DEPT. of CIVIL ENGINEERING
SOIL MECHANICS LABORATORY
CONSOLIDATION RESULTS

PROJECT THESIS
SITE U OF A
SAMPLE FAHLER CLAY
LOCATION
HOLE DEPTH
TECHNICIAN DATE

Specific Gravity of Soil Solids $G_s = 2.77$ Height of Soil Solids $H_s = .487$ ins.
Void Ratio e (End) = $2.77 : 34.3\% = 0.949$
Void Ratio e (Start) = 0.915
Void Ratio e (Start Dimensions) =

$$d) = W\%(End) \times G_s \quad H_s = \left(\frac{Wt. \text{ Soil}}{G_s \times \text{Area} \times 2.54} \right) \text{ ins.} \quad e = \text{previous } e \pm \frac{\text{Def'l.}}{H_s}$$

e	Load on	Corr. Dial	Deflection	Deflection	Void Ratio	Pressure
al	Pan (gms)	Reading (ins.)	(ins.)	H_s	e	$\text{Kg/cm}^2 = \text{T/ft}^2$
	0	.5000	0	0	.915	.0153
	20	.5652	+.0652	+0.134	1.049	.114
	100	.5577	-.0075	-0.0154	1.034	.494
	200	.5440	-.0137	-0.0281	1.006	.988
	400	.5212	-.0228	-0.0468	.959	1.976
	800	.4949	-.0263	-0.0540	.905	3.952
	1600	.4621	-.0328	-0.0674	.838	7.904
	3200	.4361	-.0260	-0.0534	.765	15.808
	6400	.4024	-.0337	-0.0692	.716	31.61
	1600	.4244	+.0220	+0.0452	.761	7.904
	400	.4556	+.0312	+0.0640	.825	1.976
	100	.4869	+.0313	+0.0643	.880	.494
	20	.5159	+.0290	+0.0595	.949	.114



B29810